Contest 2015

Title: Unknown faults under cities

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DISCLAIMER

BIBLIOGRAPHIC REFERENCE

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EXECUTIVE SUMMARY

The two most devastating earthquakes of the 2010-2011 Canterbury sequence, the September 4, 2010 Darfield and February 22, 2011 Christchurch earthquakes occurred on previously unknown faults. The 2010 event was associated with rupture of the previously unmapped Greendale Fault, 30 km away from Christchurch. The 2011 Christchurch earthquake event occurred under the city and along a fault that did not rupture to the surface. A pressing question was whether a similar scenario to the September 4, 2010 Darfield event could occur in Dunedin city. Dunedin has a similar built environment to the one Christchurch had prior to 2010, and is known to have active faults nearby (see Akatore and Titri faults in the Figure E1). In this project we assessed whether these faults, or other active faults, could extend into the city. Our efforts were motivated by the Canterbury Earthquakes Royal Commission (CERC) recommendation that “Research continues into the location of active faults near Christchurch and other population centres in New Zealand, to build as complete a picture as possible for cities and major towns”. The 2010-2011 Canterbury events demonstrated that for areas of low seismicity, it is essential to understand whether active faults may lie under or close to major cities in New Zealand.

Various lines of evidence indicate that the Akatore Fault does not extend into Dunedin city (Figure E1). We also discovered that the Titri Fault extends northwards and closer to the city than previously mapped, but it but it has buckled rather than broken the ground surface there. A newly mapped and possibly active fault, the Kaikorai Fault, lies in the western part of the city. Our interpretation is that the Kaikorai Fault most likely would rupture together with the Green Island Fault, located offshore. In contrast, our study was non-conclusive regarding the presence of potentially active faults within Otago Harbour. In low to moderate seismic areas, such the wider Dunedin area active faults can be quiescent time periods greater than 100,000 years. While the Akatore and Titri faults seem to be in an active period (from studies parallel to this one), the Kaikorai is either inactive or in a phase of inactivity (or dormant).

The research team for this project consisted of 18 researchers from GNS Science, Otago University and the Geological Survey of Spain, and included several students. The work was co-funded by the Natural Hazards Research Platform 2015 Contestable Fund, GNS Science Core Funds, University of Otago and EQC. A variety of scientific techniques were implemented to assess whether active faults extend beneath Dunedin city. Geological assessments helped find signs of sediments and rocks displaced by faults, and produce detailed maps of landscape surfaces displaced by faults. Geophysical imaging of the geological layers under the seabed and ground surface was used to determine subsurface locations where layers have been broken by faults. Measures of the Earth’s gravity discriminated whether some areas may have subsided as a result of long term fault displacements. Seismographs were installed in order to identify subtle signals of fault activity at depth. Satellite images and measurements of ground movement with GPS instruments also provided a regional perspective of active Earth’s deformation due to tectonic forces.

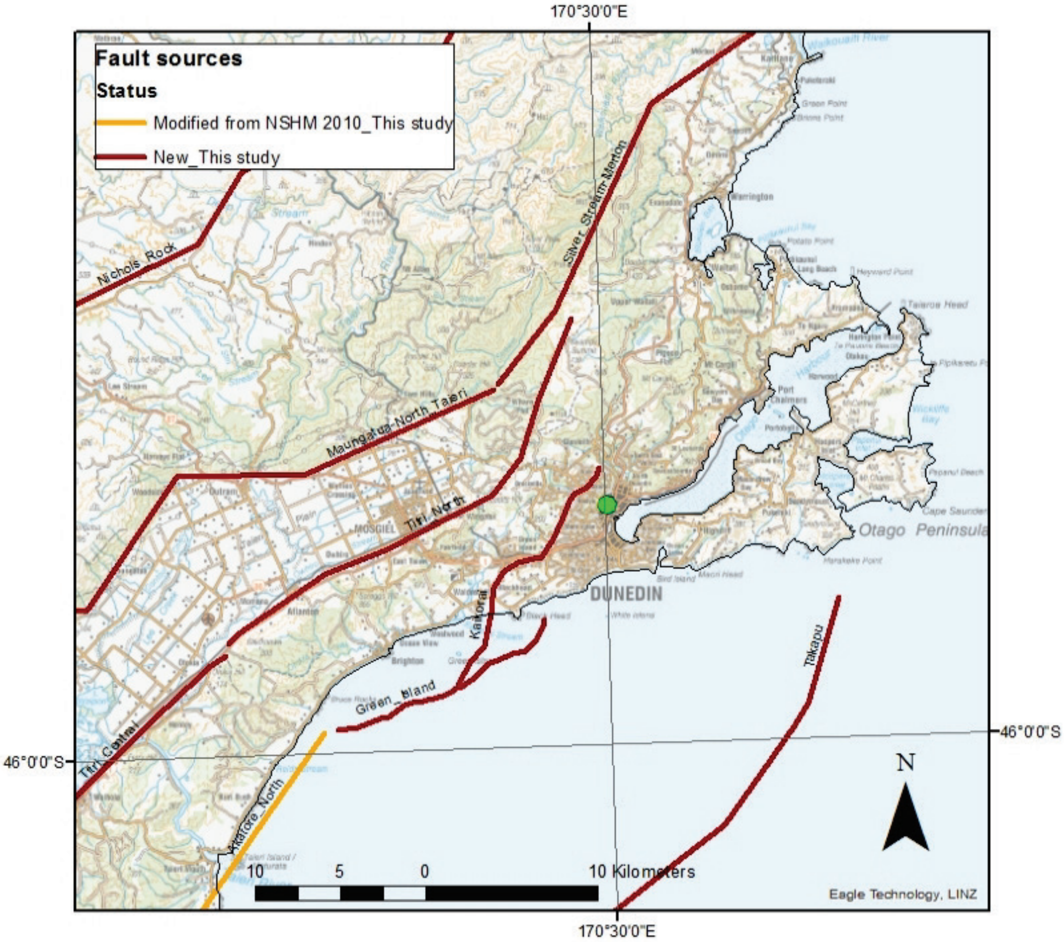

Figure E1 Location of fault sources (schematic versions of faults) around Dunedin City. NSHM, National Seismic Hazard model (Stirling et al., 2012).

In terms of the seismic hazard to Dunedin city, this study does not substantially change the levels of hazards that were estimated previously. The new faults sources we have defined have been assigned very low levels of activity. The activity of the Akatore and Titri faults (from recent studies and used here), sum up to the same value that was previously assigned to the Akatore Fault. Therefore, our hazard estimations are similar to those obtained in the National Seismic Hazard Model that informs the New Zealand Building Code. We have also assessed possible strong shaking scenarios in Dunedin from rupture of the modelled faults. Although these values have large uncertainties, it is possible that Dunedin could experience Modified Mercalli Intensity 6, and perhaps up to 8 in some parts of the city. MMIs of 6 to 8 will cause damage to unreinforced masonry buildings and could produce landslides and liquefaction in some areas. However, it is important to bear in mind that the likelihoods of rupture of these faults is low, although no lower than those of faults around Christchurch prior to 2010.

A better understanding of the presence and levels of active faults beneath, or close to, New Zealand cities is essential for appropriate and effective preparation and implementation of emergency response, more resilient land use planning and informed risk management. In low seismicity areas, presence of active faults and their level of activity are difficult to assess. Multidisciplinary projects like this help arrive to conclusions that one single technique will not be able to reach. However, we have only scratched the surface of the understanding of fault activity in Dunedin and wider region, as more data and analysis are required to reduce the uncertainty on our knowledge. With this study, we have advanced the knowledge, tested techniques that have proven useful for the purpose of finding faults under cities, and set a

base line for Dunedin city that should be revisited as new data is available. Ideally, multi-discipline, multi-agency (researchers, regional and local authorities, infrastructure owners, etc.) and multi-year (5+) programs should be established for each New Zealand City (e.g., IOF in Wellington and DEVORA in Auckland) to slowly build our knowledge around potential active faults close to our cities.

KEYWORDS

Unknown active faults, New Zealand cities, Dunedin, Royal Commission for the Canterbury Earthquakes recommendation, structural geology, gravity, seismology, GNSS, INSAR onshore and offshore seismic reflection, active fault characterisation, seismic hazard assessment.

0.0 INTRODUCTION / BACKGROUND

The two most devastating earthquakes of the 2010-2011 Canterbury sequence, the September 4, 2010 Darfield and February 22, 2011 Christchurch earthquakes occurred on unknown faults. The 2010 event was associated with fault surface rupture of the, until then unmapped, Greendale fault, but also with rupture of other smaller fault segments that did not reach the surface. The 2011 event occurred along a fault that did not reach the surface. The Canterbury Earthquakes Royal Commission (CERC) recommended that “Research continues into the location of active faults near Christchurch and other population centres in New Zealand, to build as complete a picture as possible for cities and major towns”. While New Zealand active fault research is world class and faults that accommodate most of the upper crust deformation are well known, mapped and seismically characterised, the 2010-2011 events demonstrated that for areas of low seismicity, it is essential to understanding whether active faults may lie under, or close to, the major cities.

To address the CERC recommendation, we have chosen Dunedin as a pilot study for the following reasons: a) active faults have been identified onshore and offshore that could extend into the city; b) Dunedin is a relatively compact city and thus ideal for a pilot study; c) previous and on-going work by several institutions can be leveraged to add essential value to the work proposed here; d) Dunedin has a similar building stock as Christchurch and thus similar losses and damage could be expected as a consequence of fault rupture under or in close proximity to the city.

To address the potential presence of active faults and characterisation as earthquake sources, a complex multidisciplinary approach is required because no single discipline on its own will be able to find a solution. We will also trial some techniques that may either be relatively new or difficult to apply to low seismicity areas, with the aim that the integrated results will yield a robust research answer. Focusing on Dunedin is thus well-timed and will also help perfecting the techniques before rolling out to areas where active faults may be more difficult to find (e.g., Auckland).

The goals of the research proposed here are: 1) to assess whether there are active faults in two areas of suspected fault activity (see below); 2) assess the deformation rate across the city including two suspected fault zones; and 3) seismically characterise the faults (if active) and improve hazard estimates for the city of Dunedin. Two possibilities have been considered for the extension of the active Akatore Fault northward into Dunedin city: 1) along Kaikorai Estuary and Kaikorai valley and into Waitati valley (KWL); and 2) into South Dunedin and along Otago Harbour (OHL). Another parallel structure was identified 3 km farther offshore, the Green Island Fault and any potential on-land extension is also unknown. An overriding goal of the research is also to test the viability of a number of different techniques for identifying hidden faults in urban areas.

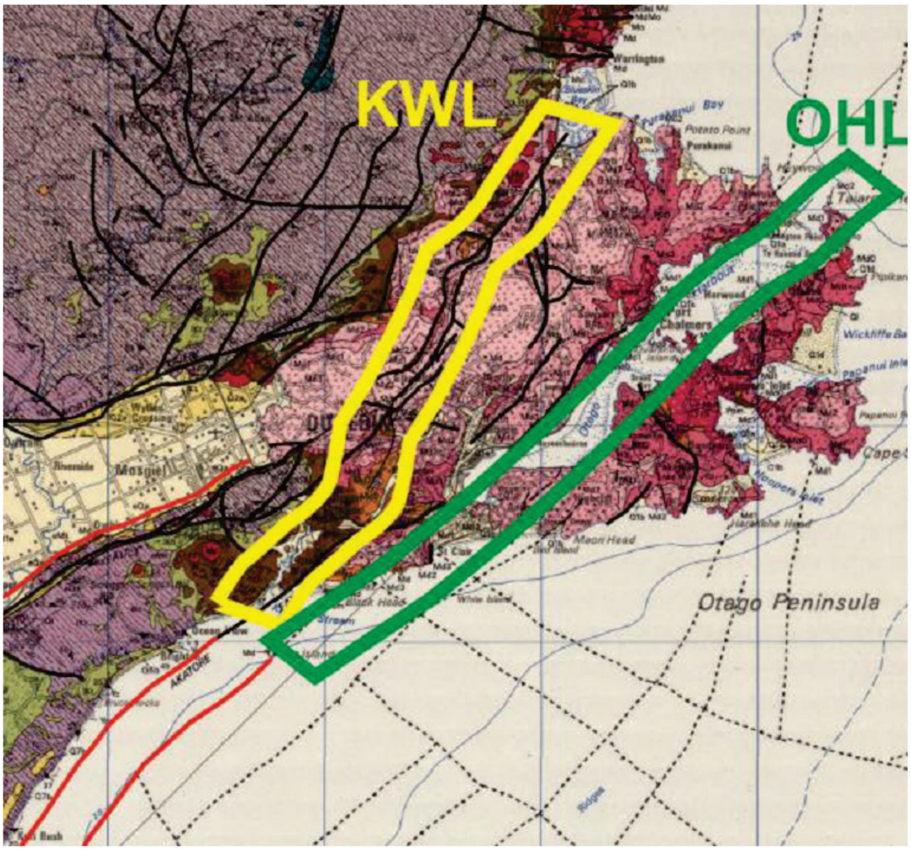

Figure 1.0.1 Locations of the Kaikorai-Waitati lineament (KWL) and Otago Harbour lineament (OHL) plotted on the 1:250,000-scale geological map (Bishop and Turnbull 1996). The blue grid lines have a 10 km spacing.

1.0 TITLE - IMPACT STATEMENT 1

The newly defined earthquake sources in Dunedin city are incorporated in to the New Zealand Building Code through their assimilation into the National Seismic Hazard Model. Otago Regional Council Hazard Plans are informed by the new Seismic Hazard Map of Dunedin. Local authorities and McDEM utilise the new information of earthquake sources and hazard in Dunedin to improve future land use and to better prepare and respond to a major earthquake. This will be achieved through a programme divided into 4 main areas: 1) Scale and nature of fault(s) and their potential as earthquake sources: Surface and subsurface tectonic structure of Dunedin City; 2) Potential seismicity rates associated with active fault(s): Rates of crustal deformation in Dunedin City; 3) Seismic characterisation of earthquake

1.1 Research Aim: Geological Study

Title: Acquisition and analysis of new geological data to address if the KWL is a potential earthquake source and presents a seismic hazard

Budget: $68,570[1]

Research Aim achieved? Yes

Discuss

Research aim description: We will collect structural data, mainly from the Tertiary sediments, and refine structural contours of key surfaces to constrain the tectonic deformation in the Dunedin area, and the surface geometry and potential kinematics of the KWL in particular. Structural data and potential offsets will be evaluated to determine whether or not the KWL is favourably oriented for slip in the current stress regime. Structural data will be added to current mapping and 3D model of the area and results included in the final report. This task will benefit from the current integration of existing geological and geophysical data (3D Geology Map of Dunedin) undertaken under GNS Science SSIF Funds (MURG Programme.).

Results

To evaluate the geological evidence for an active fault along the KWL, we undertook new field work and reviewed and compiled existing geological mapping. A detailed account of this work is provided in Appendix 1. In this section we summarise the key results.

Our field studies were focussed on the western side of the upper Leith Valley sector of the KWL where previous geological maps (Benson, 1969) showed two faults. We did not observe any faults in the region and suggest the geological observations are best fit by a steeply-dipping package of strata with no faults involved.

The review and compilation of existing geological mapping has resulted in the production of a map of structural contours (or isolines of equal topographic elevation) on distinctive geological boundaries. Where certain those boundaries have significant offsets or steep gradients in elevation, we can make interpretations about the nature of the deformation. In particular, structural contours help to resolve locations of potential faults. The structure contouring, together with field observation and literature review, has identified faults around Dunedin that could potentially be active (see details in Appendix 1). The results of this work are illustrated ion (Figure 1.1.1).

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1 Budget reported here and for other Research Aims shows contributions from NHRP exclusively. In the whole project, additional NZ $400,000 were contributed by GNS Science, University of Otago and EQC.

The largest in terms of amplitude, and with high confidence of its existence, is the Titri Anticline, a large up-fold representing a northern continuation, in the subsurface, of the Titri Fault. The next most significant feature is identified as the Kaikorai Fault, whose presence is most robustly indicated by a ~60-80 m difference in the elevation of the base of the Dunedin Volcanic Group either side of Kaikorai valley. We provisionally interpret the Kaikorai Fault to be a northeast-striking fault upthrown to the southeast. Minor faulting close to the line of the Kaikorai Fault was identified in bedrock by Barrell and Litchfield (2013), but it was not certain whether those minor faults are of tectonic or slope movement origin.

There is less certainty regarding the Blackhead Fault and Ravensbourne Fault because the differences in rock type either side of each fault could possibly be due to geological processes other than faulting (see further details in Appendix 1). If real, the Blackhead Fault and Ravensbourne Fault coincide approximately with the OHL (Figure 1.0.1), but we consider that based on existing information, their identification is highly uncertain.

The Leith Syncline, a gentle down-fold, is interpreted to mark the northeastern limit of uplift on the Kaikorai Fault, as well as the eastern margin of the Titri Anticline uplift. The structure contouring indicates that a zone of steeply dipping volcanic rock in Leith valley, previously interpreted to mark the location of a fault, is too localised to represent a separate, independent, fault. Instead, it is now thought to be a locally over-steepened zone on the eastern limb of the Titri Anticline.

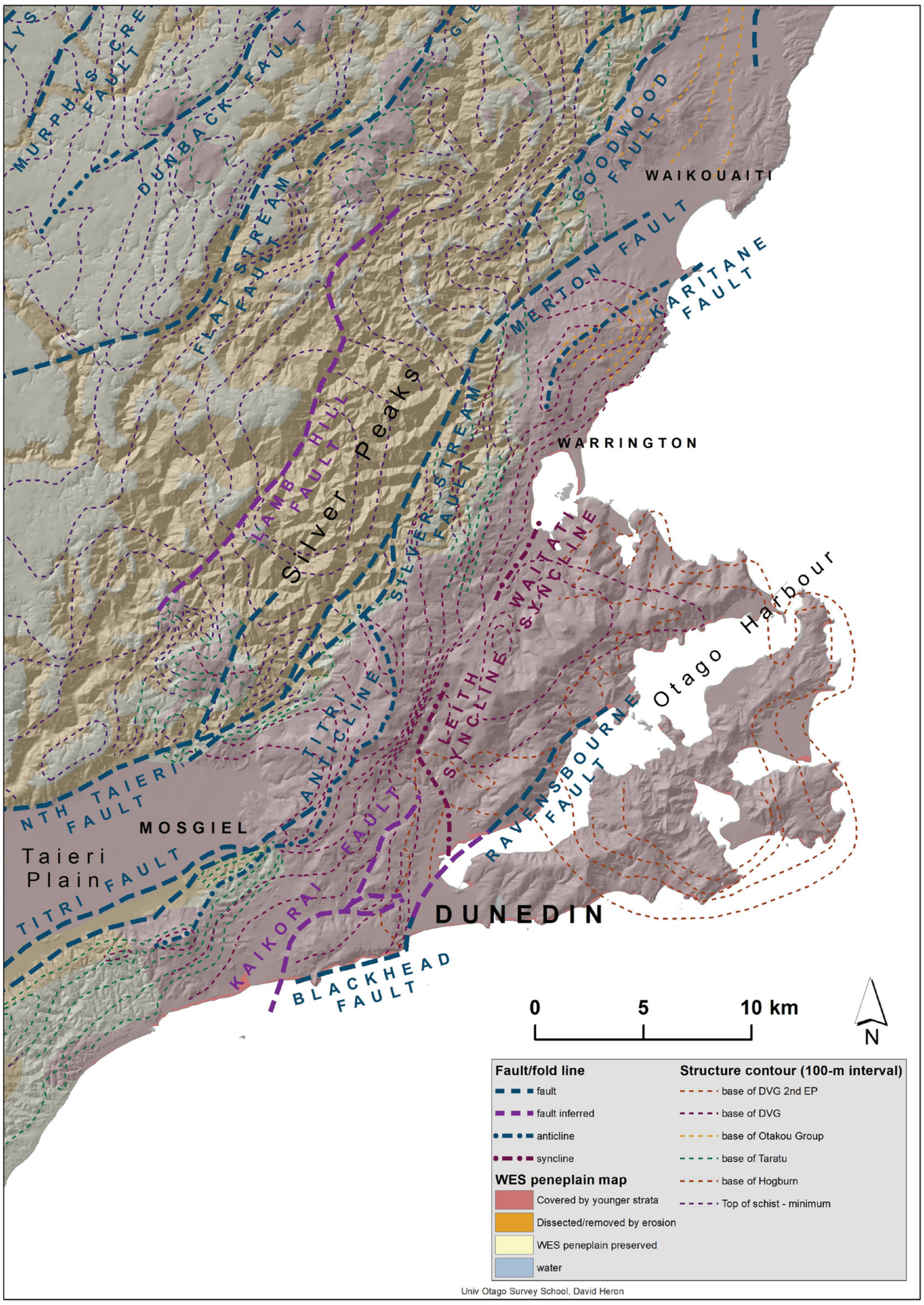


Figure 1.1.1 Structure contour map for the wider Dunedin area. See Figure A1.1.3 in Appendix 1 for description of map components.

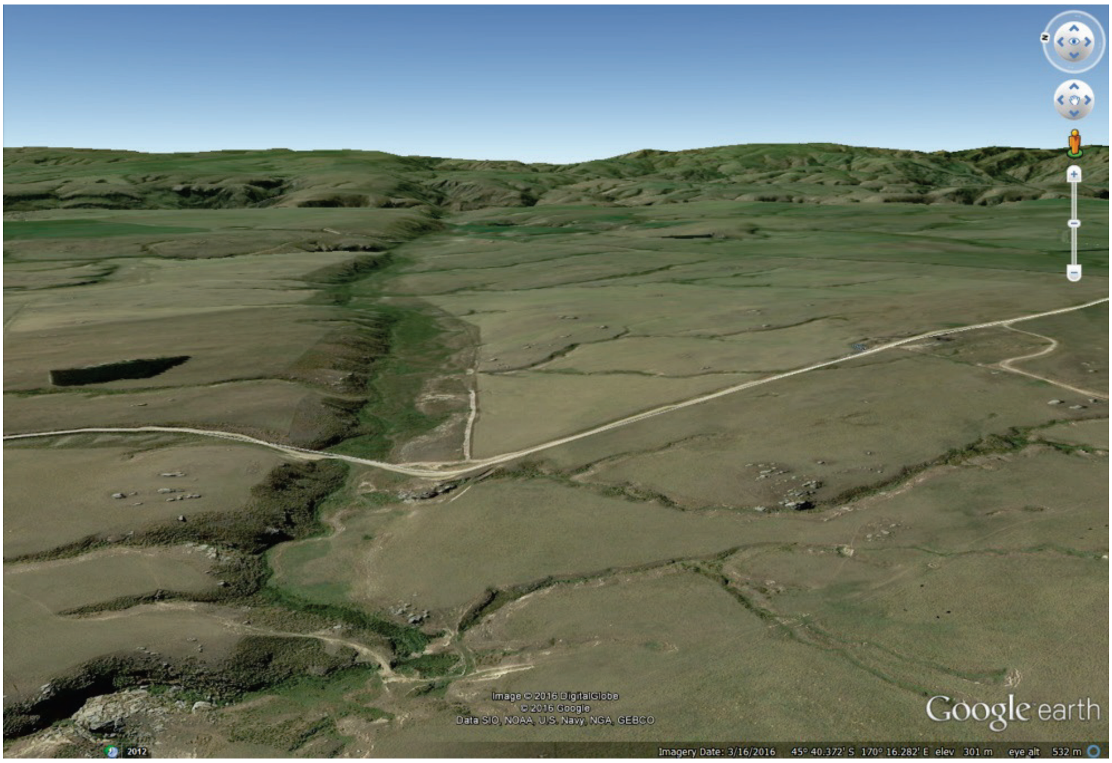


Figure 1.1.2 Google Earth image looking northeast along the Flat Stream Fault. Barewood Road is in the foreground. The smooth land surface in the fore to middle ground is a remnant of the paleoerosion surface on schist basement (WES), which is displaced 10-20 m, up to the NW (left) by the Flat Stream fault. The prominence of the fault escarpment is primarily a function of the ancient land surface (its fundamental character is at least as old as 23 millions of years) developed on hard schist rock. There is no indication of whether or not this fault has moved in the last 125,000 years.

Potential Activity of the KWL

The largest fault close to Dunedin city is the Titri Fault. To the south the Titri Fault has experienced Quaternary-age surface ruptures, but the geological relationships indicate that to the north, it becomes a blind fault underlying a large-scale up-fold (Titri Anticline). We conclude that the KWL is not associated with a single geological structure, but rather is a linear coincidence of several features. These comprise, in the northeast, the Waitati and Leith synclinal troughs at the southeastern margin of Titri Anticline uplift, and in the southeast, the Kaikorai Fault block. Our preliminary interpretation is that the Leith and Waitati synclines are passive features that are not directly associated with an underlying fault. Farther south along the KWL is the inferred Kaikorai Fault, upthrown to the southeast. The topographic elevation of that side of the fault may be a primary tectonic morphology, although it may have component of differential erosion that enhances the tectonic offset. Although it has a similar orientation and sense of throw to the Akatore Fault, there is good reason to regard them separate structures, as addressed in Research Aim 1.8. Of particular importance is that the Akatore Fault has experienced multiple Holocene ruptures, but it is clear from the lack of landform disruption that the Kaikorai Fault has not experienced Holocene rupture, nor does it show any direct evidence for Quaternary offsets. The Kaikorai Fault is nonetheless identified as a potentially active fault, but due to its indicated short length, is thought to link with the offshore Green Island Fault.

List of outputs

- New field structural data acquired and new structural contour map created.
- Data interpretation with definition of major Late Quaternary Cenozoic faults.
- Barrell (2016) - Geoscience Society of New Zealand conference abstract.

1.2 Research Aim: Offshore seismic reflection study

Title: Acquisition and analysis of offshore seismic reflection data to improve understanding of fault activity and recurrence period of the Akatore and Green Island faults (OHL) and assess potential extension of the Akatore Fault into the KWL

Budget: $15,000

Research Aim achieved? Yes

Discuss

Research aim description: We aim to acquire offshore data (multibeam, side scan sonar and boomer) to better constrain the transition zone between the Akatore and Green Island faults in the OHL region. This will help assess the continuation of the Akatore Fault and how deformation is transferred between the two faults. We also aim to better constrain the amount of throw on the offshore Akatore and Green Island faults (boomer and side scan sonar data). We will also obtain offshore seismic reflection data as close as possible to the Kaikorai Estuary to complement the pilot onshore seismic reflection study (see Research Aim 1.3) to assess the possible extension of the Akatore Fault into the KML. These data will be integrated into an Otago University MSc thesis. Analysis of new and existing data will help to assess the seismic activity of the Akatore and Green Island faults, their structure and their relation to the current tectonic regime. This information will be relevant to the assessment of the deformation rates across Dunedin (see Research Aim 1.9) This Research Aim benefits from relevant data obtained by OU student training surveys, BSc and MSc studies since 2004.

Results

Offshore surveys and data compilation

A compilation of offshore high-resolution seismic data along the coast south of Dunedin has been completed as part of an MSc project (Holt, 2017) to assess possible offshore continuation of the Akatore Fault (Litchfield and Norris 2000; Gorman et al., 2013) and better define the Green Island Fault (Bruce 2010). New and existing data were where compiled in under the same database (Figure 1.2.1) and most of it reprocessed (in part, through the application of direct arrival picks), which greatly improved the resolution of the images and the seismic velocities. Over the last two years, we have acquired roughly 200 km of new high-resolution seismic reflection data along the Otago coast with the University of Otago's 24-channel boomer system aboard RV Polaris II to image the subsurface. This has been complemented by new multibeam data to image seafloor features. Weather and sea state conditions precluded the collection of new data specifically in the vicinity of the Green Island Fault and beach at the Kaikorai Estuary but this is still a high priority for ongoing work.

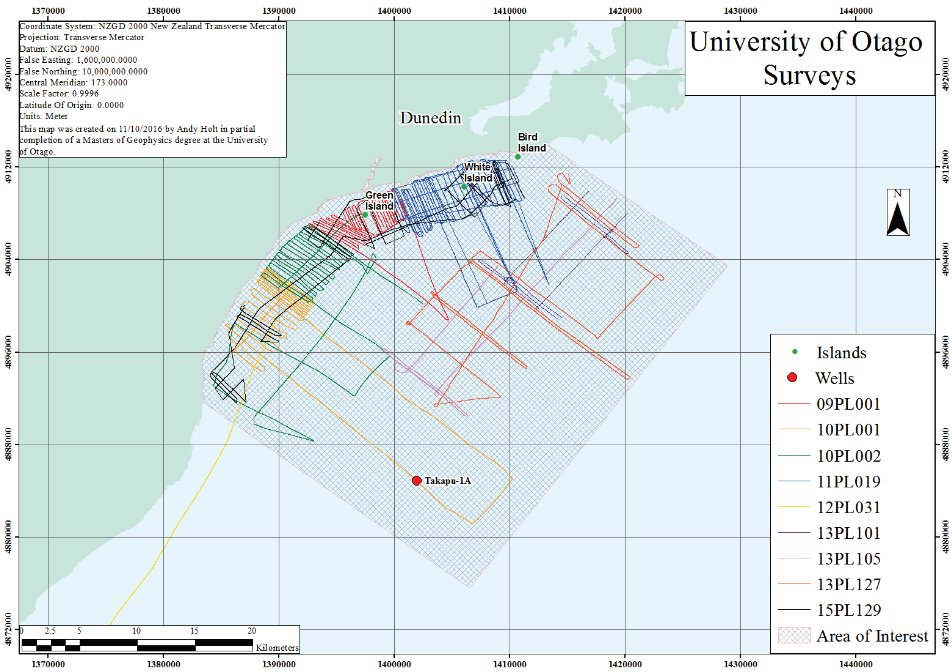


Figure 1.2.1 High-resolution boomer seismic lines that are being used to intepret the extent and of the offshore Akatore and Green Island faults.

Update of the Akatore and Green Island faults offshore

An update of the location of the Akatore and Green Island faults has been achieved by identification of the faults along each profile. We have identified tectonic features (faults, folds) and qualitatively assessed the likelihood that they are tectonic (certain, possible, uncertain) (Figure 1.2.2).

Based on this interpretation, the Akatore Fault can be mapped to extend 11 km offshore from it northernmost coastal location (Figure 1.2.2 and Figure 1.2.3). The offshore Green Island Fault is probably an active structure. Evidence for this is provided by a fault rupture interpreted through single channel seismic data. Combined analysis of multi-channel seismic and sidescan sonar datasets supports this interpretation. This fault is interpreted to be at least 9 km long with an undetermined total offset between the two fault blocks and is located 3 km offshore, to the SE of the Kaikorai Estuary. The possible onshore extension of the Akatore Fault at Kaikorai has not been observed due to the limitations of this type of seismic survey in shallow waters (within the surf zone) close to the coast. However, the total offset of the Akatore Fault seems to decrease to the north whereas offset on the Green Island Fault increases in the same direction. This switch of total displacement between the two faults could suggest that deformation is taken up by the Green Island Fault and that the Akatore Fault does not extend into the KWL (or the Kaikorai Fault). The scarcity of preserved Quaternary sediments precludes characterisation of fault activity rates in this area.

Due to thick mobile seafloor sediments, the seismic reflection lines at the mouth of Otago Harbour proved to be inconclusive in terms of imaging active structures. New data are currently being acquired in the harbour that may be able to address the presence or absence of active faulting along the harbour (OHL; see more on the assessment of fault activity onshore at Ravensbourne to Port Chambers in Research Aim 1.8).

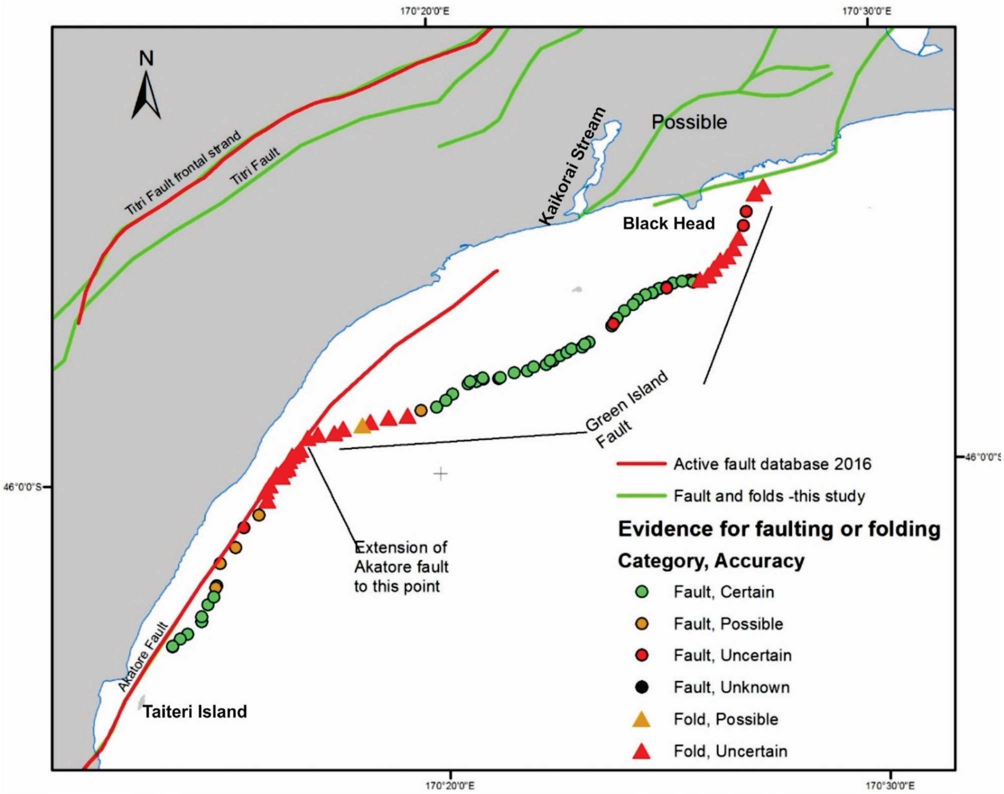


Figure 1.2.2 Locations where faults or folds have been interpreted from offshore seismic reflection (subsurface strata) data. Tectonic deformation of sedimentary layers is clear in some locations (features labelled as "certain"),whereas in other places, interpretations of structural features (folds and faults) is difficult due to a lack of signal penetration or reflective units. In such cases, fault locations are considered "possible" (Figure 1.2.2). While the sedimentary units imaged here are likely to be Late Cretaceous to Neogene in age, structures are interpreted as being much younger.

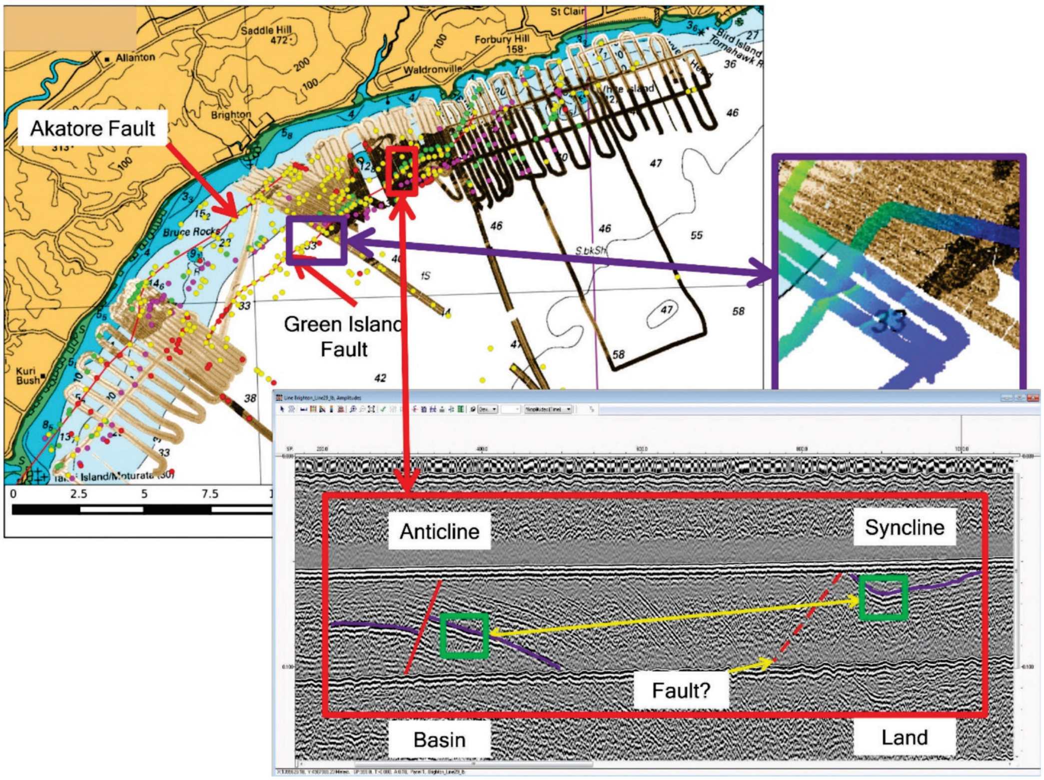


Figure 1.2.3 Update of the location of the Akatore and Green Island faults offshore (top left). Note that red dots indicate the clear presence of faulting in the seismic profiles, whereas yellow dots indicate possible faulting. The match between seismic reflection information and multibeam data is clear (top right); this image shows the fault scarp displacing the ocean floor. An interpreted seismic reflection profile (bottom) shows the complexity of the interpretation of tectonic vs sedimentary features, which makes the estimates of fault throw uncertain.

List of outputs

- Compilation and reprocessing of existing and new seismic reflection data into a useable georeferenced database
- Acquisition of new offshore seismic reflection and multibeam data
- Holt and Gorman (2015). Geoscience Society of New Zealand conference abstract. Preliminary map of offshore Akatore and Green Island Faults.
- Holt, A. 2017. Acoustic investigations of geologic hazards and seismic processing off the coast of Otago, New Zealand. Unpublished MSc Thesis, University of Otago, 205p.
- A paper based on the results of Holt's thesis is currently in preparation.

1.3 Research Aim: Onshore seismic reflection study

Title: Acquisition and analysis of new onshore seismic reflection data to assess possible extension of the Akatore fault into the KWL

Budget: $20,750

Research Aim achieved? Yes

Discuss

Research Aim description: We aim to trial a seismic weight-drop source system, newly developed by University of Otago in the Kaikorai Valley immediately onshore of the Kaikorai estuary. This pilot study aims to assess the ability of, and optimize the equipment for imaging Quaternary sediments and potential sediment deformation in association with the suspected onshore continuation of the Akatore Fault into the Kaikorai Valley as suggested by Bishop and Turnbull (1996). This study is linked to a research proposal submitted to Otago Regional Council to undertake onshore seismic reflection studies in South Dunedin.

Results

As part of this pilot study a 3-km-long seismic reflection line along the coast at Kaikorai Estuary was acquired (Figure 1.3.1 and Figure 1.3.2). The acquisition occurred in stages (from August 2016 to May 2017) as access to site and surveying was dependent on weather and tide conditions, and on access permissions from various authorities. Acquisition was undertaken as part of the University of Otago's GEOL261/361 field school. Initial data processing was undertaken by a former MSc student, Patrick Lepine, but subsequently the interpretation and analysis become part of a new MSc thesis by Catherine Sangster.

Imaging of faults in the near subsurface with the seismic weight-drop source system, is it useful?

The Kaikorai Esturary seismic reflection line, together with other three lines collected outside the scope of this study (Bathgate Park and King's High School, see Holt and Gorman, 2015; Kettle Park; Dunedin Railway corridor; all part of Sangster's MSc project thesis; Sangster in prep.) (Figure 1.3.1) have demonstrated that the seismic weight-drop source system produces successful results. In the Dunedin geological environment, we were able to obtain P-wave reflection images of the surface strata down to depth of about 250 m with a vertical resolution of about 20 m. With such imaging quality, significant fault displacements of strata should be identified if present. This is a robust tool to further investigate the present or absence of active faults under Dunedin city.

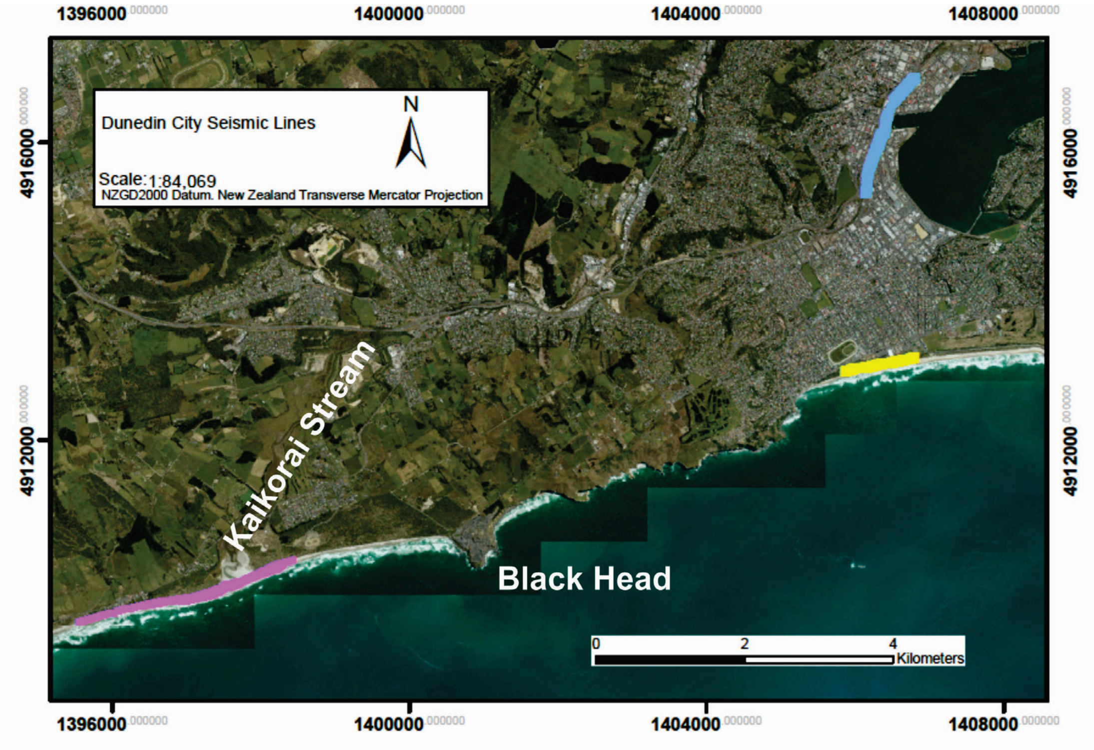


Figure 1.3.1 Seismic weight-drop source system survey locations. Dunedin Railway Corridor line in blue. Kettle Park line in yellow. Kaikorai Estuary beach line in pink. Note that the Kaikorai Estuary line was funded by this study. The other lines used the same methods and are incorporated into Sangster in prep.

Does the offshore Akatore Fault continue into the Kaikorai Valley? Does the newly mapped Kaikorai Fault continue offshore?

The offshore investigation undertaken in this project (Research Aim 1.2) suggests that the offshore Akatore Fault may transfer deformation eastward to the Green Island Fault. Therefore, it appears that the Akarore Fault does not extend into the Kaikorai valley.

However, the seismic line collected at the mouth of the Kaikorai Estuary presents an opportunity to evaluate if the newly mapped Kaikorai Fault extends offshore. Gently folded strata are clearly visible in the seismic line (Figure 1.3.3 and Figure 1.3.4) with an overall inclination toward the east. Although faulting is not observed on the seismic line, the tilt of the sediments could be associated with movement of a fault to the east of the line, which is a possible location of the Kaikorai Fault under the young beach dunes.

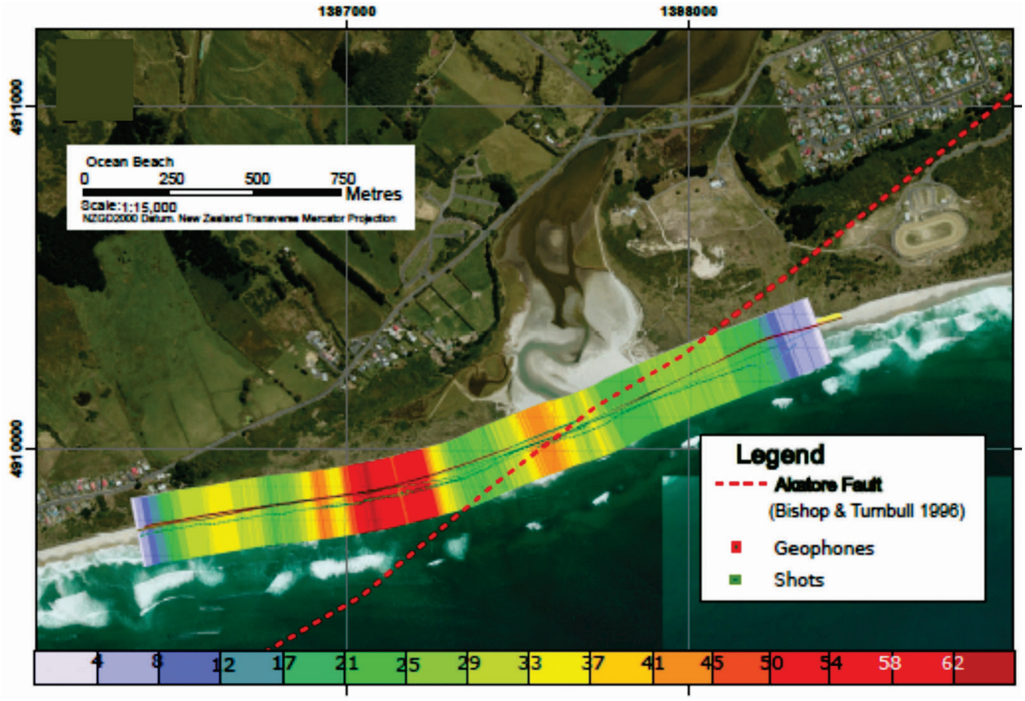


Figure 1.3.2 Detailed location of Kaikorai Estuary beach seismic line. The red dashed line indicates the interpreted location of the Akatore Fault before this survey was conducted (Bishop and Turnbull 1996). The green dots show the locations of the geophones, the sensors which detected the seismic energy. The red dots show the locations of where the seismic weight-drop source (the thumper) impacts. These are referred to as shots. The seismic fold (redundancy of common midpoint seismic data) along the line is displayed in a multicoloured strip with values indicated by the colour bar. The fold display is extended out from the line to show the width of the CMP bins used in the processing.

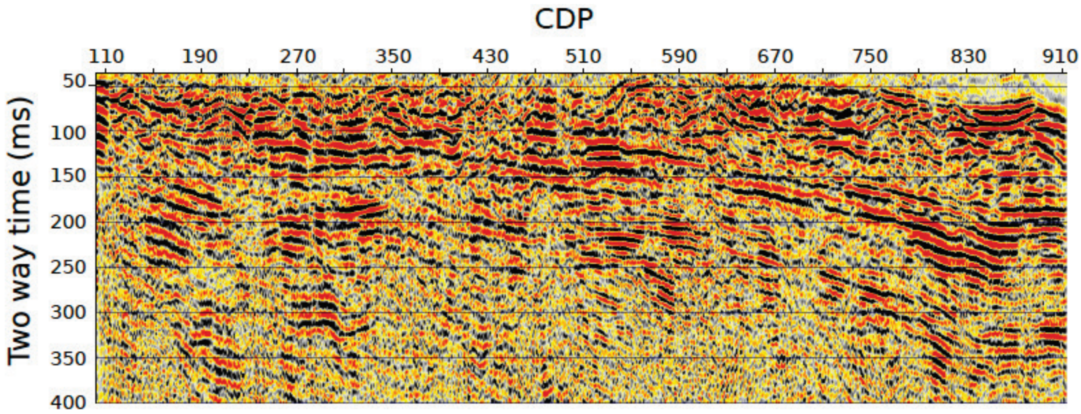


Figure 1.3.3 Kaikorai Estuary beach seismic line. Raw stack with limited processing. CDP spacing 2.5 m. See Figure 1.3.4 for interpretations.

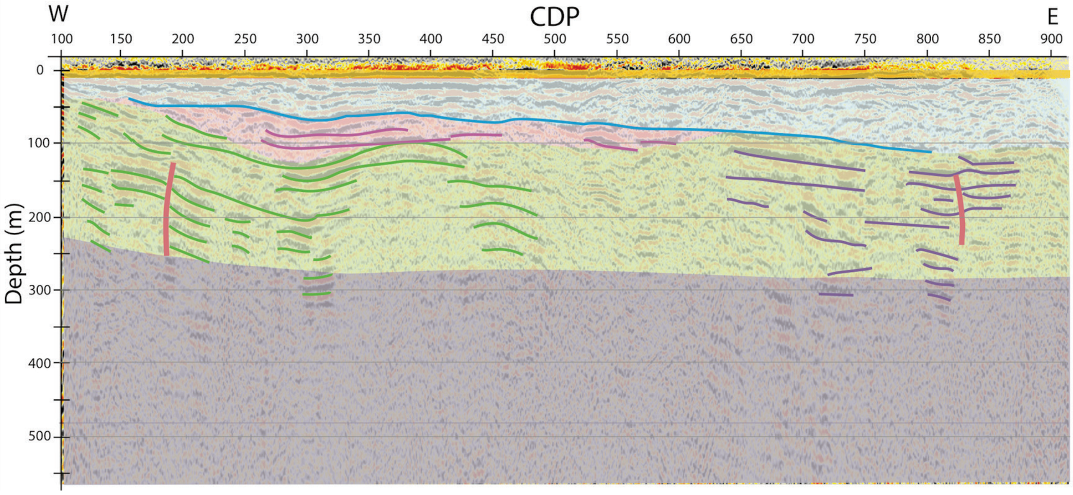


Figure 1.3.4 Kaikorai Estuary beach seismic line. Depth converted migrated stack with interpreted stratigraphic and basement geological units. Interpreted units, tied to regional surface outcrop maps, are: orange (near surface modern beach sediments); blue (Plio-Pleistocene sedimentary units sitting on top of an unconformity); pink and green (Upper Cretaceous and Neogene sedimentary units, with the basal part including reflective coal beds within Taratu Formation); grey (Otago Schist basement).

List of outputs

- 3 km long onshore (Kaikorai Estuary) weight-drop sourced seismic reflection line acquired and interpreted.
- Capability development with: a) further training of Patrick Lepine, former Masters student at the University of Otago; and b) commencement of new MSc study, Catherine Sangster at the University of Otago. c) Involvement of University of Otago's GEOL261/361 field school students.
- Holt and Gorman (2015). Geoscience Society of New Zealand conference abstract.

1.4 Research Aim: Passive seismicity study

Title: Acquisition and analysis of new seismic data from a sensitive passive seismic array to be able to locate microseismicity and tremor along the KWL and the OHL.

Budget: $39,400

Research Aim achieved? Yes

Discuss

Research Aim description: The existence of microseismicity and/or tremor is a robust indicator of activity on a fault. They have been associated with active faults even in low seismicity areas. Dense arrays have been shown to be very effective at finding M≤1microseismicity in the crust as well as mapping tremor radiation on faults that were locked on the surface but 'creeping' at depth (e.g. Wang et al., 2013). We will apply a method using an array of arrays in which 3-4 mini-arrays with ~10 broadband seismometers will be deployed. This approach was first successfully applied to determine accurate tremor locations deep within the Cascadia subduction zone (Ghosh et al., 2009). In this method, data from each mini-array are stacked to increase the amplitude of the signal to a level that is observable about the noise background. The location of the deployment will be determined in consultation with geologists and geodesists and in agreement with preliminarily results from Year 1. Complementary analysis of the array data for local velocity structure will also be undertaken through co-alignment of core-funded research. Results on potential seismic activity of the two lineaments from the passive seismic experiment will be incorporated into the final report. This task will also benefit from results of the ongoing Marsden project led by M. Reyners (GNS) on deep crustal properties of the Otago Region. Analysis an interpretation of Marsden data will occur during Year 1 of the study proposed here and will contribute to design of the sensitive passive experiment and analysis of data.

Results

Discrimination of earthquake signal from background noise.

If movement occurs on a fault within the seismogenic region (from about the surface to about 15 km depth), the fault will most likely radiate seismic energy. However, it is possible that this seismic energy will be too weak to be detected by traditional seismic arrays. In fact, in many areas of New Zealand, the minimum magnitude of earthquake that we are confident that the permanent GeoNet network will detect is larger than M3. This precludes the use of the GeoNet network to search for micro-seismic evidence of fault activity, and thus we have designed an experiment with clusters of densely spaced seismometers (or “dense arrays”).

The passive experiment was designed to detect microseismicity from both Kaikorai-Waitati and Otago Harbour lineaments. The network was an “array of arrays”, which comprised three microarrays or stations with 6 seismometers each surrounding the two lineaments (Figure 1.4.1; refer to Fig. 0.1 for lineament location). The arrays recorded over a 3-month period (July -September 2016) window, with different subsets of data recording at various times. By the end of the 3-month period each station had recorded a total of 20-25 days of data.

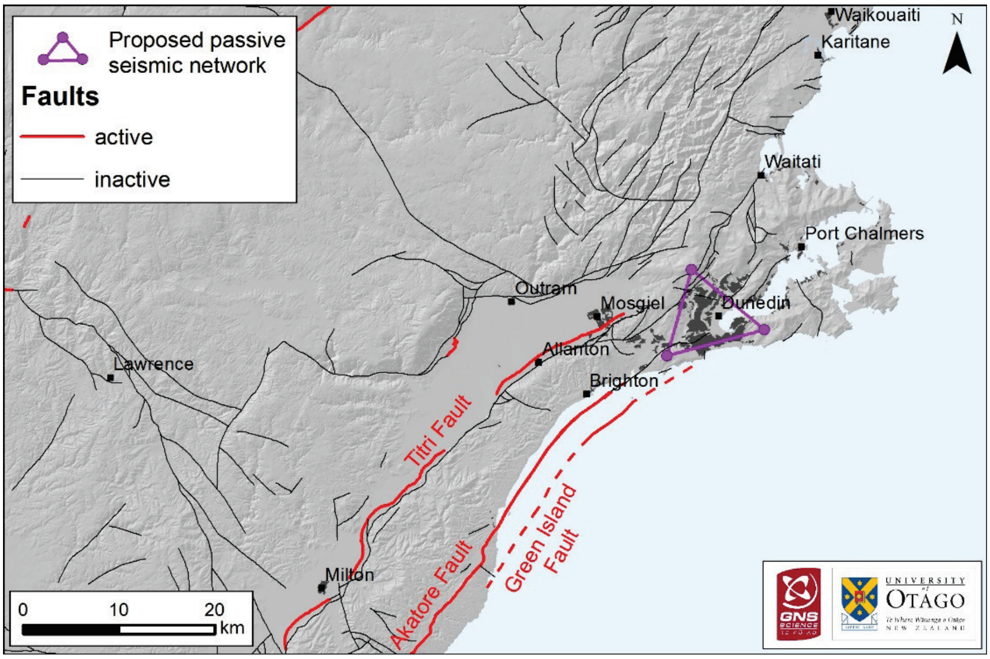


Figure 1.4.1 Seismic network for passive seismic experiment. Purple circles are location of the three stations. Each station contained 6 seismometers. Active faults from NZ Active fault database (Langridge et al., 2016). Inactive faults as per regional geological mapping (Bishop and Turnbull, 1996; Forsyth, 2001).

These data were analysed with both dense-array and traditional sparse array approaches. We searched the continuous data for coherent energy (signal from micro-earthquakes) within each dense array cluster (Figure 1.4.2). In this method, incoherent energy (noise) from each seismic channel within the mini-array is minimized and coherent energy (signal) is isolated. This process can elevate coherent signals associated with microseismicity and tremor above the noise background. The coherence of the signal was then queried for potential origin directions within and outside the network. The second approach applied to the data was a network analysis in which short-term (seconds) spikes in amplitudes of ground velocity recorded at the stations were associated with earthquake when at least 6 of the stations recorded spikes within a time window that spanned all possible time delays for earthquakes within the southern South Island. These time delays were calculated through the 3D New Zealand wide model (Eberhart-Phillips et al. 2010). A non-linear algorithm was then used to locate the most likely hypocentre through a smart grid search.

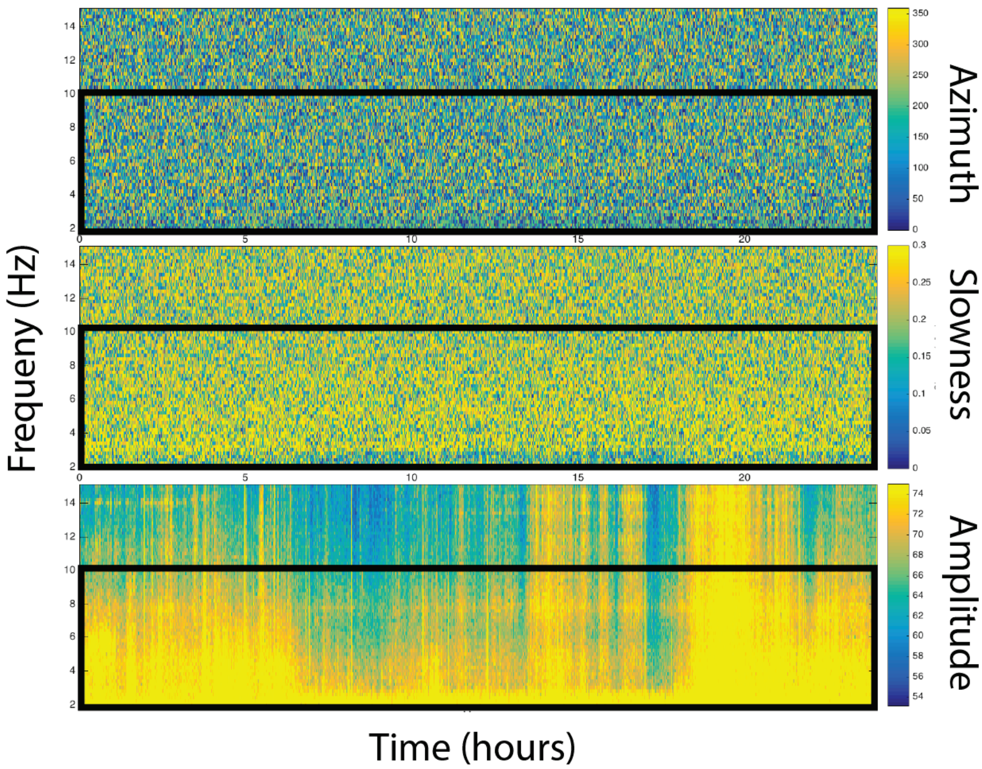


Figure 1.4.2 Example day showing the recorded energy from one of the clusters. In this plot, energy recorded over the earthquake and tremor frequency bands (black boxes) is clearly visible in the bottom panel, as yellow regions. However, If this energy were recorded within the network, as would be the case if generated on the OHL or KWL, distinct horizontal bands would be obvious in the top two panels.

Is there microseismicity along the Kaikorai-Waitati and Otago Harbour lineaments?

Our observations suggest that the KWL and OHL lineaments do not seem to be currently producing seismicity. Processing and analysis of data suggests that while seismic waves within the micro-earthquake and tremor frequency bandwidth have been detected by the network, the waves seem to have been located far away from the arrays (Figure 1.4.3). Both the dense array and network approaches (see below) support this conclusion.

When used in addition to broadband data from GeoNet operated stations throughout the southern South Island, data from the arrays contribute to the detection and location of earthquakes during the deployment period by increasing the number of events detected and improving the detection of small (M 1-2) events in eastern Otago and Southland. We employed an automatic detection algorithm similar to the method used by GeoNet on a national scale to detect earthquakes in addition to manual earthquake detection throughout the duration of the network deployment. Events detected by the array are shown in Figure 1.4.3.

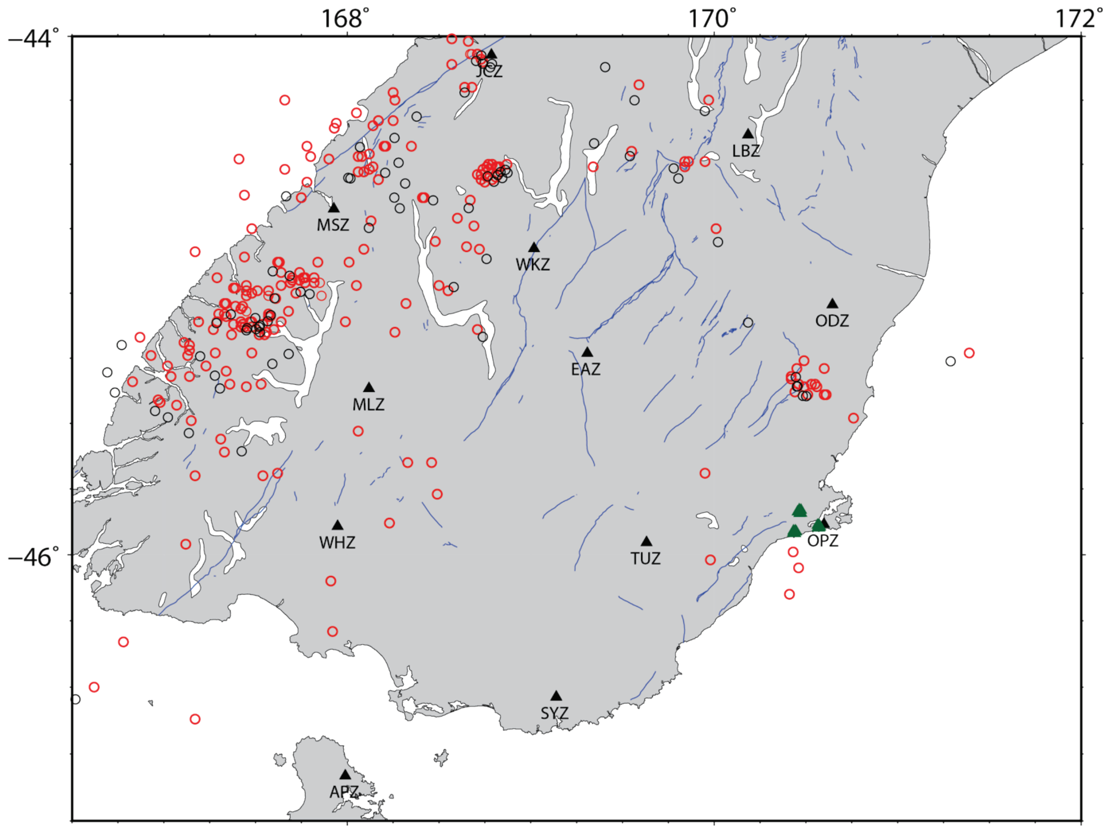


Figure 1.4.3 Earthquakes (red circles) detected throughout the southern South Island between 26 July 2016 and 3 September 2016 with Dunedin passive seismic arrays (green triangles) and GeoNet operated seismic stations (black triangles). Blue lines are active faults from the NZ Active Fault Database (Langridge et al., 2016). Black circles are earthquakes from the GeoNet catalogue. The combination of data from the Dunedin arrays and GeoNet broadband stations detected more earthquakes than the GeoNet stations on their own, especially in eastern Otago.

List of outputs

- Dense-array seismic database created from 3 months of data collected on subsets of 18 seismometers, with 20-25 days of data recorded on each seismometer.
- Capability development:1) Students from Otago University helped with deployment and servicing of stations and collection of data; 2) Postdoctoral Scholar Erin Todd (University of Otago) was trained to undertake data processing and analysis.
- GNS Science has implemented slowness based dense array processing.

1.5 Research Aim: Gravity study

Title: Acquisition and analysis of new gravity data to complement the understanding of the subsurface geology in the Dunedin area.

Budget: $50,170

Research Aim achieved? Yes

Discuss

Research Aim description: This study aims to evaluate if gravity anomalies can be associated with potentially active faults and or areas of potential tectonic uplift. We aim to add around 80 new gravity measurements to the current gravity data base in and around Dunedin city with the goal of densifying the coverage to a 1 to 1.5 km spacing (current coverage has around a 3 km spacing and there is a zone with no data). We also aim to acquire gravity measurements offshore in conjunction with the offshore seismic reflection surveys undertaken in Research Aim 1.2. This study benefits from the use of the existing gravity database (approximately 150 gravity stations) already existing in the study area.

Results

Acquisition of new data and new gravity maps

Eighty-four gravity readings, including repeated stations, were collected using a portable gravity meter in the Dunedin region in December 2015. Lidar data and high-resolution imagery were used respectively to provide heights for gravity processing and accurate location information for some stations. Sixty-two usable discrete gravity station readings resulting from the field measurements (locations shown in Figure 1.5.1) have been processed. A Bouguer anomaly map has been produced (Figure 1.5.1). The Bouguer anomaly highlights areas with sediment and rock of different density, and thus it is useful to identify those faults that have materials of different density juxtaposed across the fault plane.

Presence or absence of active faults from gravity data

The most obvious feature of Figure 1.5.2 is the Bouguer high (red colours) which approximates the main bulk of the relatively dense Dunedin Volcano (delimited by a dashed circle in the Figure) which was modelled by Reilly (1972). Around this there seems to be a round Bouguer low (blue and green colours) which may represent a moat structure of Dunedin Volcano. Some areas of the moat do not have a dense cover of gravity measurements and thus this interpretation is preliminary. This feature is likely to be a result from the contrast in density between near surface volcanic and sedimentary rocks. It is thus not related to active faulting. Beneath Dunedin City and South Dunedin, the gravity is relatively constant indicating no underlying large vertical fault-offset of basement (Figure 1.5.3A).

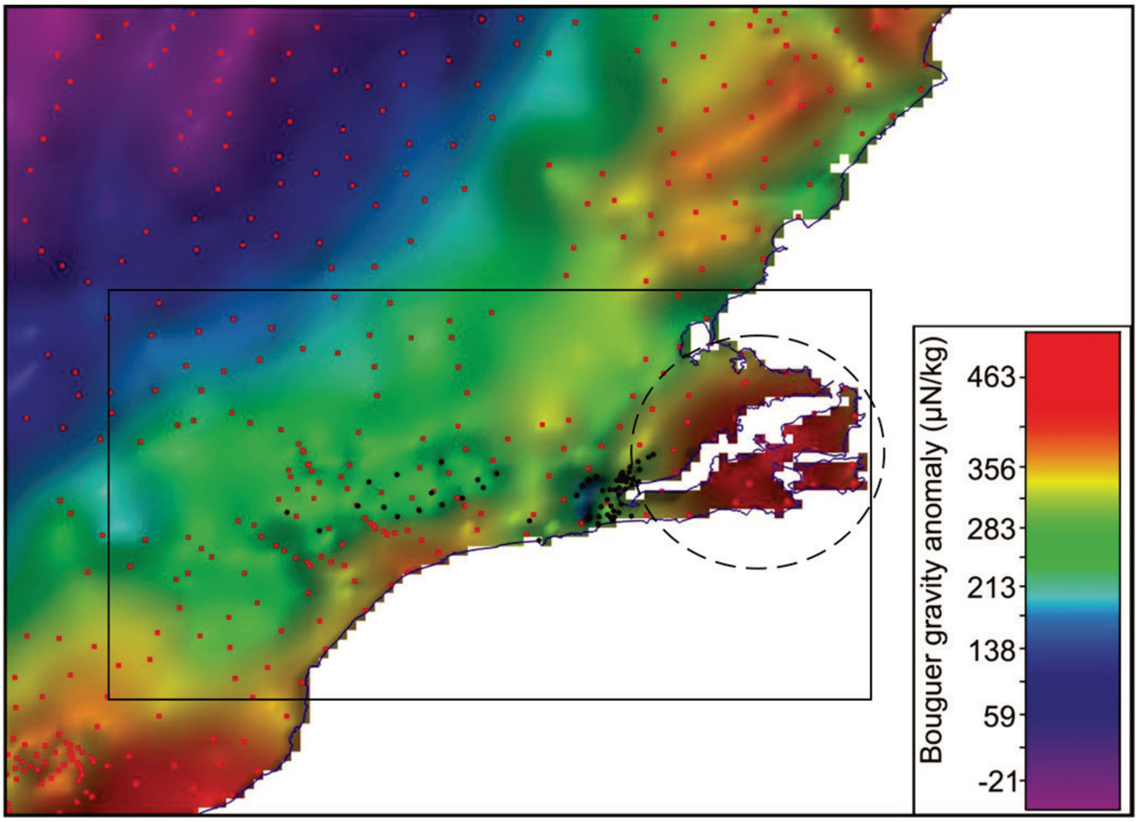


Figure 1.5.1 A run-shaded Bouguer gravity anomaly image derived from combining existing GNS Science national gravity database points (red squares) and recently acquired data (black circles). The image has been gridded at 1 km intervals. Black rectangle is location of Figure 1.5.2.

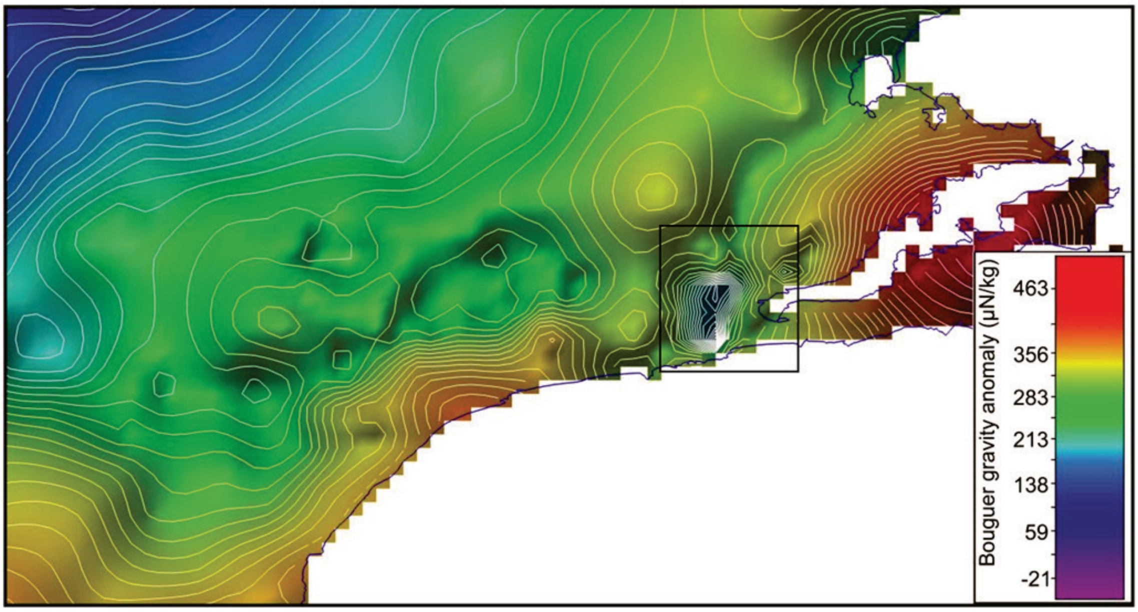


Figure 1.5.2 A 10 mgal contoured sun-shaded image of Bouguer gravity anomaly derived as for Figure 1.5.1. Black rectangle is location of Figure 1.5.3.

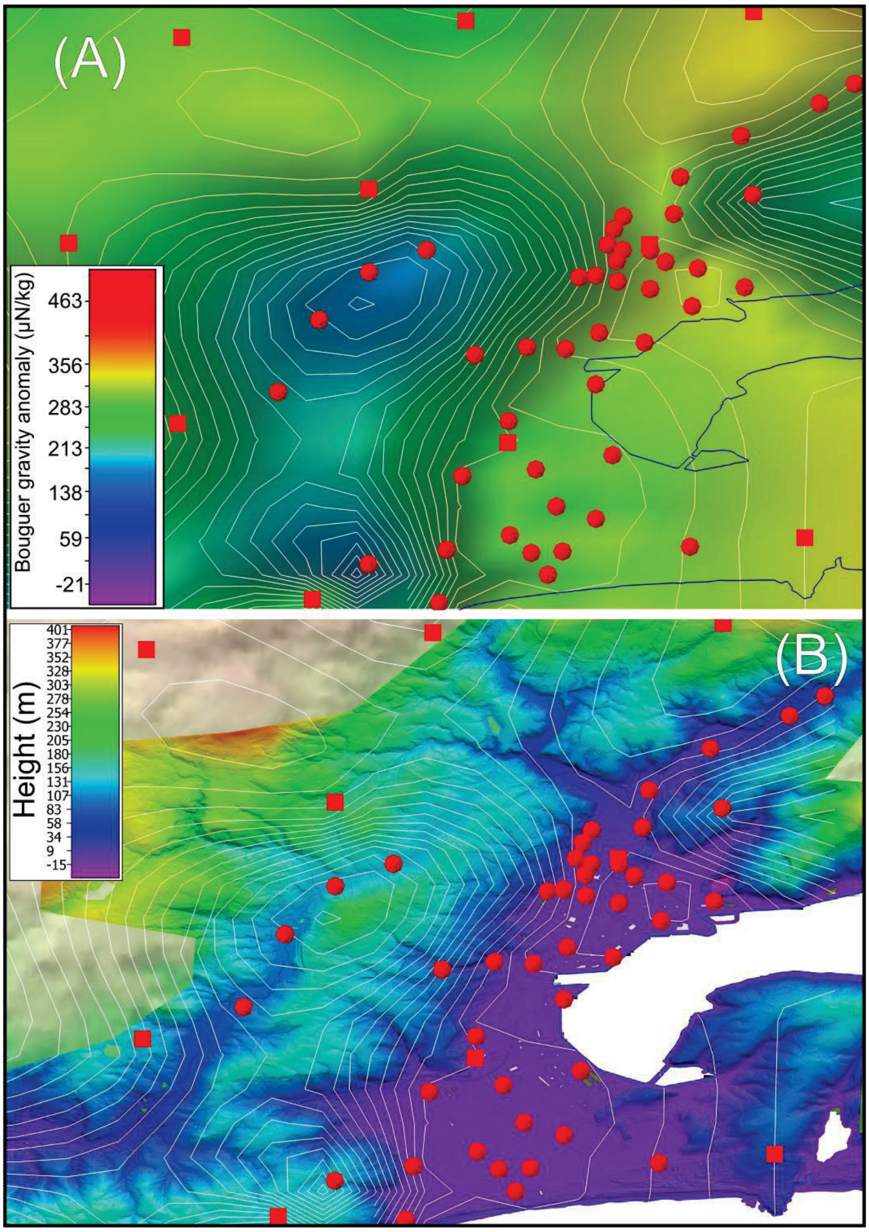


Figure 1.5.3 (A) Sun-illuminated Bouguer gravity anomaly image of the Dunedin City region overlain by 5 µN/kg interval contours. Red dots are data locations for gravity collected in December 2015. Red squares are existing data in the GNS Science gravity database. (B) Sun-illuminated Lidar and regional topography of the Dunedin City region. Colour is this figure denotes topographic elevation. White lines are 5 µN/kg interval contours of Bouguer gravity anomaly (A).

List of outputs

- Sixty-two new gravity measurements collected and incorporated in the National Gravity Database.
- Bouguer anomaly map of the wider Dunedin area produced.

1.6 Research Aim: Geodetic study

Title: Acquisition and analysis of existing and new geodetic data to measure the crustal strain across Dunedin city to assess if deformation occurs across the KWL and the OHL and constrain slip rates and locking depth

Budget: $19,500

Research Aim achieved? Yes

Discuss

Research Aim description: In areas of low seismicity such as Dunedin city, GPS measurements need to be recorded for a minimum of 3 to 4 years to be able to obtain a value that is above the noise level. We will mainly use existing data recorded by two of the permanent stations in Dunedin (OUSD from 1995 and DUND 2005 onwards) and by the regional network of campaign GPS sites of UO (built up and measured yearly since 2004) to assess crustal deformation rates across Dunedin city. We will build a new permanent GPS station at a suitable site, near an existing regional campaign site, just north of the Dunedin city and add the continuous record of two years along with the existing campaign data to the analysis. With this new station, we will set up a profile for evaluating crustal deformation in close proximity to Dunedin that can be used in future studies to assess changes in deformation in conjunction with the regional campaign GPS network of OU. In addition to the existing regional campaign network, a sub network of up to 20 stations will be installed in and around Dunedin city by UO to be measured in a rapid semi continuous mode, three stations at a time, each measured for two months with fixed monuments to minimize setup errors. This study will benefit from on-going data acquisition and analysis of the Otago Regional Network (set up and measured by OU) and partial funding from GNS CORE funded Programme "Tectonics and Structure of Zealandia". This project will work closely with Research Aim 1.7 "InSAR analysis". Results will be incorporated to final report.

Results

New continuous and semi continuous Global Navigation Satellite System (GNSS) stations

In December 2015 a network of 11 stations suitable for semi continuous measurements (threaded rod) was installed around the city (labelled as SC in Figure 1.6.1). The sites have been measured once a year (see Figure 1.6.2 and Figure 1.6.3 Lower) with total measurements between 39-72 days, spanning between 1.7 and 2.1 years. In March 2017, a new continuous GNSS (cGNSS) monument was installed 38 km north west of Dunedin city (SUTT in Figure 1.6.1; funding from EQC). The station became fully operational in June 2017 but we have some data from March 2017 (1.3 years) (Figure 1.6.2 and Figure 1.6.3 Upper).

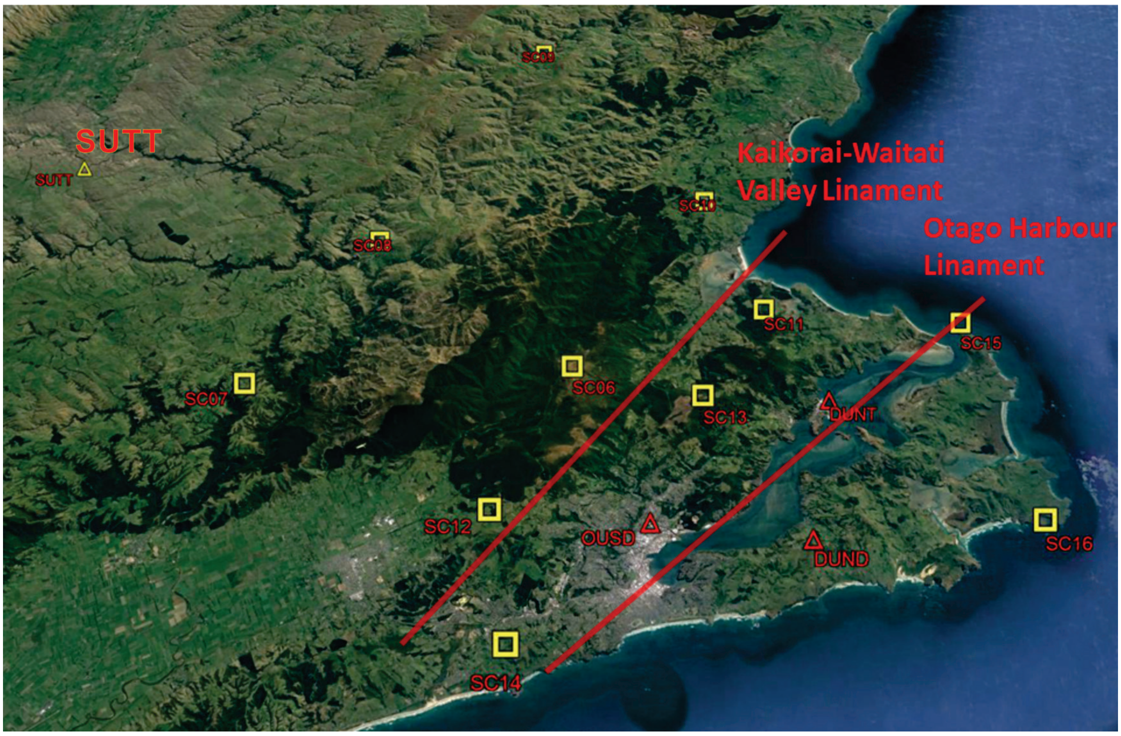


Figure 1.6.1 Locations of new cGNSS site, SUTT, (yellow triangle), new Dunedin network (yellow square) and existing cGNSS sites (red triangle). Red solid lines are the two lineaments targeted in this project.

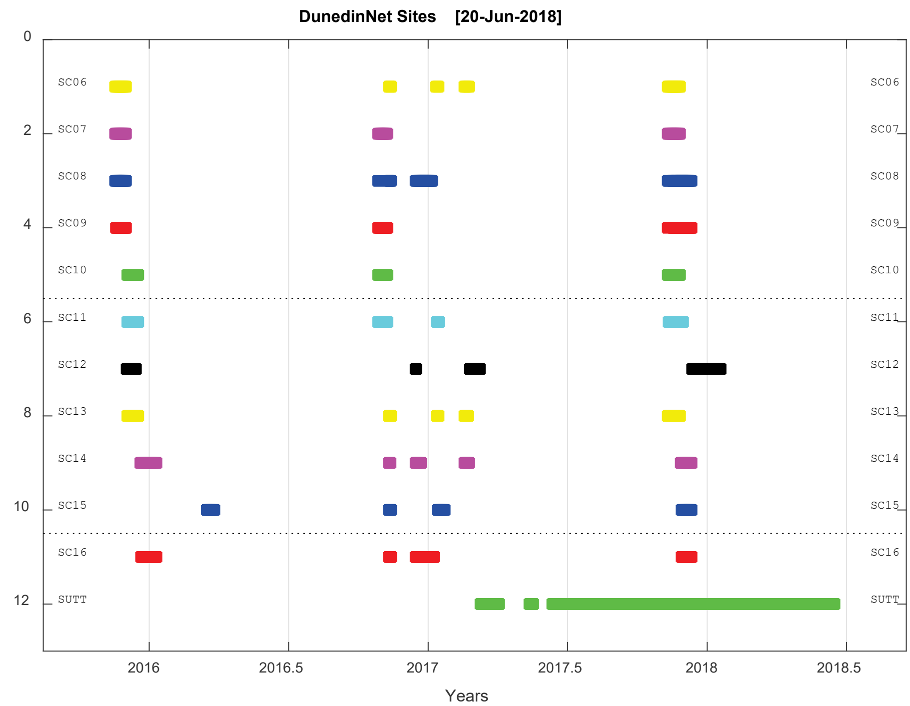
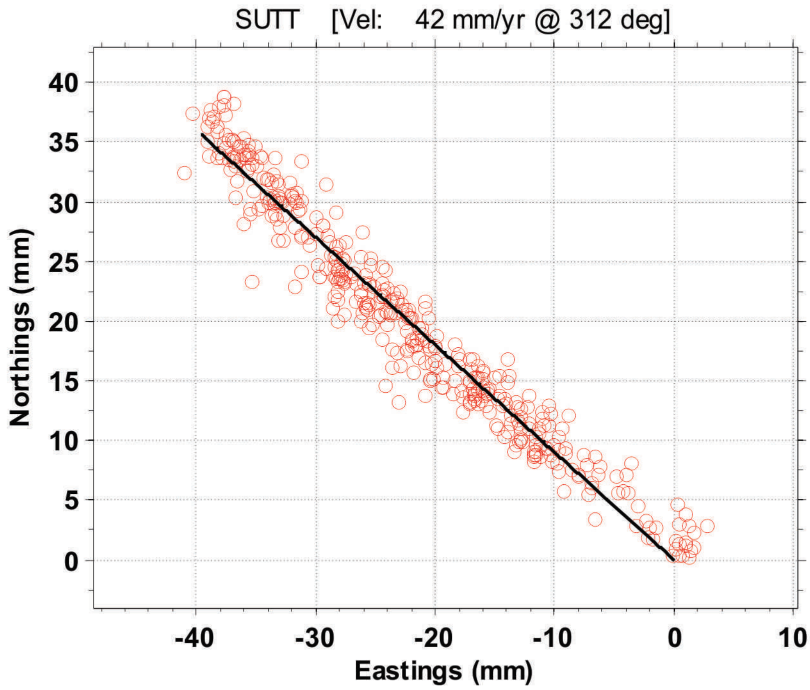


Figure 1.6.2 Time recordings for the new GNSS stations, installed as part of this project.



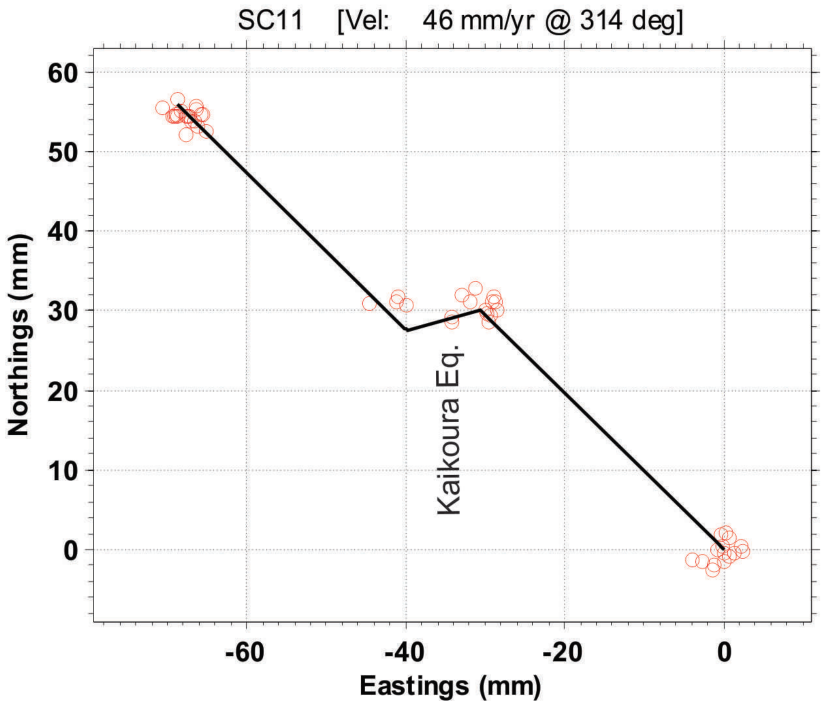


Figure 1.6.3 Upper) Horizontal position time series for the new cGNSS site, Sutton (SUTT) using data from March 2017 to June 2018 (1.3 years). The estimated rate of 42 mm/yr @ 312°, based on 1.3 years of data, is only slightly different to the long term cGNSS sites OUSD (44 mm/yr @ 314°) and DUND (45 mm/yr @ 313°). Lower) Horizontal position time series for the Dunedin network campaign site Mopanui (SC11). Data collected in December 2015, November 2016 and November 2017. This site had data collected before and after the Kaikoura 2016 and clearly shows a positional shift of approximately 8 mm.

What is the deformation rate across the Dunedin area from GNSS data

In low to moderate seismicity areas such as Dunedin, GNSS data must extend over 4.5 or more years to be able to reduce the GNSS velocity uncertainties sufficiently to detect reliable velocity differences across the region of interest. While we were aware of the short time frame of this project (approximately 2 years), we aimed to be able to use new short-term data in conjunction with existing data to evaluate deformation rates across the Dunedin region. Unfortunately, that has not been possible at this stage because: (1) there was a delay in the installation of the cGNSS station at Sutton (SUTT); (2) the times series for the campaign stations are not sufficiently long to be reliable; and; (3) more importantly, the effects that recent major South Island earthquakes have on the data records. The Dunedin area has been significantly affected by the movement related to a few major earthquakes (e.g. 2004 Macquarie Island, 2007 George Sound, 2009 Dusky Sound, 2010 Darfield, 2016 Kaikoura Earthquakes). The 2009 Dusky sound earthquake still affects the deformation in the region due to post-earthquake response of the Earth's mantle and the 2016 Kaikoura earthquake struck in late 2016 causing a few mm offset at all sites in the Dunedin region (e.g., Figure 1.6.3 Lower). As a result of these issues we have instead evaluated a preliminary deformation rate across the area looking at pre-Dusky earthquake continuous GNSS data. This has reduced the data to the time window of 4.5 years

Our preliminary deformation rate across the Dunedin area is at least 1.0 mm/yr (in a vectoral direction 100°) (Figure 1.6.4). The velocity field obtained is shown in Figure 1.6.3. We obtained pre-2009 estimates of ~5.4 mm/yr for LEXA cGNSS station and ~3.0 mm/yr for cGNSS OUSD. Therefore, the difference between the sites is 2.4 ± 0.5 mm/yr (in a vectorial direction 077°). These values are influenced by the current loading of crustal stress (Earth's forces) on the Alpine Fault, which affects most of the South Island. We have undertaken a simple calculation to remove this effect, and we find that the effect of the Alpine Fault results on an additional 1.0 mm/yr (in vectorial direction 230°) at the LEXA station in comparison to the OUSD station. We have thus removed (vectorial subtraction) 1 mm/yr to the value above (2.4 mm/year) to obtain a preliminary deformation rate between LEXA and OUSD stations. Our final estimate of 1 mm/year of relative movement across the wider Dunedin region is very low relative to the tectonic plate rate of ~ 35 mm/yr at the Dunedin latitude.

While we have not been able to utilise the data from the new GNSS stations in this study, we believe this project greatly improves the GNSS monitoring around one of the New Zealand large cities. Continued surveying of these stations will produce sound monitoring of earth deformation across Dunedin and will help assess the tectonic subsidence and uplift at the coast. This will set up a baseline to monitor Earth movements around Dunedin and will greatly contribute to better informed seismic hazard and sea level rise assessments in the future.

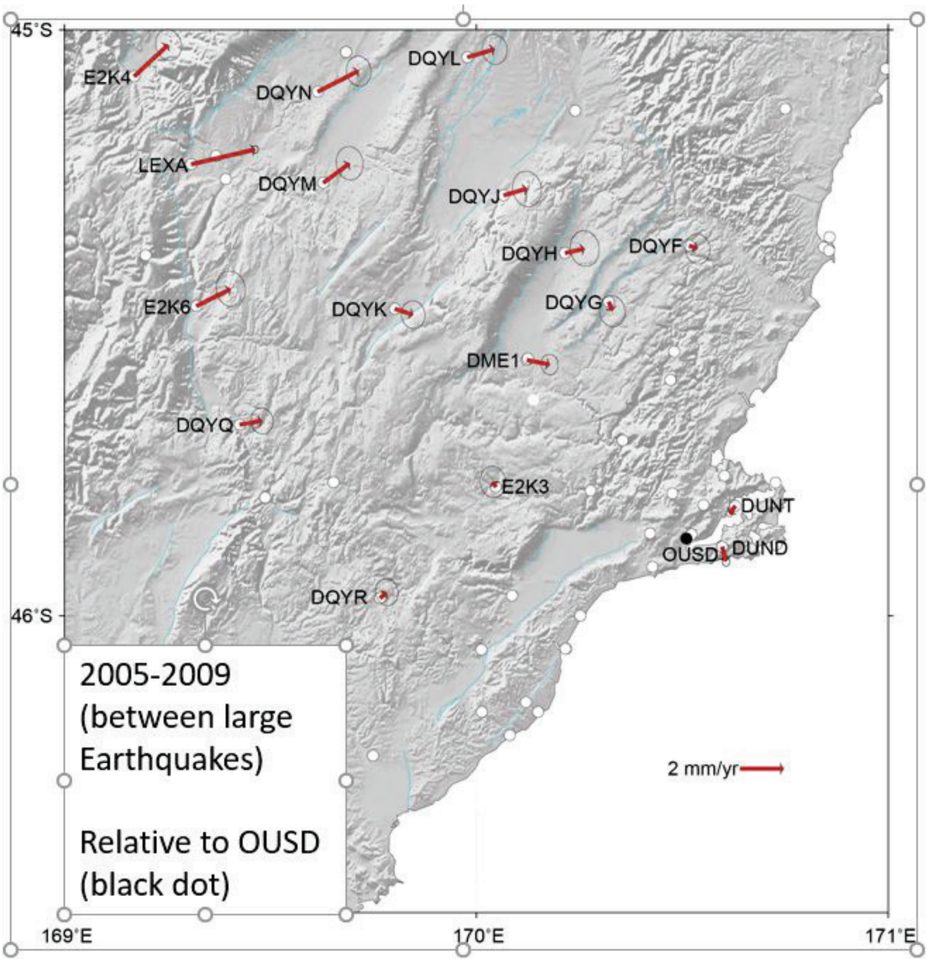


Figure 1.6.4 Velocities obtained from reprocessing of GNSS data collected prior to the 2009 Dusky Sound Earthquake. Velocities are relative to the cGNSS station OUSD.

List of outputs

- GNSS monitoring network around Dunedin upgraded with 11 new campaign and one continuous GNSS stations.
- New GNSS datasets from campaign network (11 stations with for 39 to 74 days of data per station and one continuous station (since June 2017) added to the national GNSS database.
- Preliminary tectonic deformation rate across Dunedin assessed.

1.7 Research Aim: InSAR study

Title: Analysis of existing InSAR data in the wider Dunedin region to assess how surface crustal deformation is accommodated in Dunedin city and in particular across the KML and the OHL

Budget: $21,000

Research Aim achieved? Yes

Discuss

Research aim description: We will use images from the European Space Agency's Envisar satellite dating acquired between 2003 and 2010 to assess potential surface deformation across Dunedin city. While the deformation rates resolvable can be variable depending on the distribution of acquisitions and the length scale of the deformation, by applying time series methodologies we should be able to detect rates approaching 1mm/yr. In the event that we are unable to detect a signal related to potential strain accumulation, we will use forward models to investigate the range of slip rates and locking depths that would be needed in order for us not to detect a signal. We will assess InSAR data in conjunction with GPS data (Research Aim 1.6).

Results

Data processed and generation of velocity maps

Across the Dunedin region, there were 91 Envisat Synthetic Aperture Radar (SAR) scenes acquired across 3 ascending tracks from 2003 to 2010. We have focused on tracks 137 and 409 (Figure 1.7.1) where the majority of images were acquired and provide better spatial coverage of the Dunedin region. To generate an interferogram, we compare the phase information from radar signals produced by satellites orbiting ~700 km above the Earth. In the event of the ground moving in the time between the image acquisitions, we detect a change in the distance between the ground and the satellite allowing us to measure millimetre scale surface displacements over thousands of square kilometres. Across Dunedin we formed 280 interferograms, 140 on each of the satellite tracks. Due to variations in water vapour in the atmosphere, which delays the passage of the radar signal and creates orbital errors, we ground truthed the InSAR displacements using the GNSS velocity field. Using the displacement information from each of the interferograms, we can then extract the best fitting velocity for points on the ground. Because of the looking direction of the satellite, the InSAR derived displacements are measured in the satellites Line-of-sight (LOS). Here positive displacements indicate an increase in path length (ground moving away from the satellite) and negative displacements are toward the satellite (ground moving towards satellite). To turn the LOS displacement maps into vertical displacement maps, we isolated the vertical component of the displacement field by removing the expected horizontal velocities measured independently using GNSS (Figure 1.7.2 to Figure 1.7.4).

Figure 1.7.1 Envisat ascending tracks 137 and 409 covering the wider Dunedin region.

Surface deformation across Dunedin city and surroundings

Values of uplift and subsidence are generally low as expected from a low deformation area; although locally there are some large values. The InSAR derived velocities are consistent with the limited continuously operating GNNS in the area. Both InSAR datasets indicate that the area of reclaimed land in South Dunedin is subsiding at rates approaching 5 mm/yr (Figure 1.7.2). Because the subsidence focussed over a small area, it not likely to be tectonic in origin. Within Central Otago, there is evidence of localised landsliding 5 km south of Waipiata as well as some motion within the Moeraki township (Figure 1.7.3, Figure 1.7.4).

Across the major active faults south of Dunedin, the Titri and Akatore faults, we do not see any evidence of motion (Figure 1.7.3 and Figure 1.7.4). This suggests that neither of the faults are currently creeping at the surface and that that the faults, if slipping at depth, are below the resolvable limit of the InSAR data consistent with paleoearthquake derived slip rates. However, given the errors in the InSAR measurement and the low geological (thousands of years) slip rate, it is possible that any signal associated with the faults at depth is unresolvable by the currently available InSAR data.

While the InSAR images have not proved useful to detect tectonic movements in the Dunedin area due to low deformation rates, they are consistent with the GNSS results of Research Aim 1.6 indicating that current deformation across the region is overall low. In the future, new data acquired every 12-days from the European Space Agency's Sentinel mission will allow us to resolve smaller displacement rates than possible with existing data and provide new constraints on the deformation around Dunedin and the rest of New Zealand.

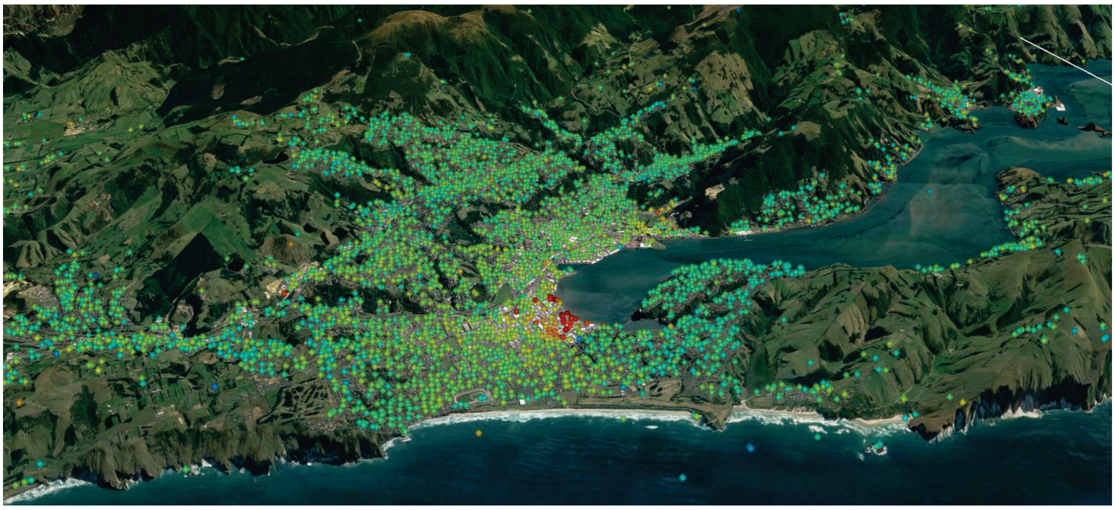


Figure 1.7.2 Velocity map of land movements from InSAR data in Dunedin City.

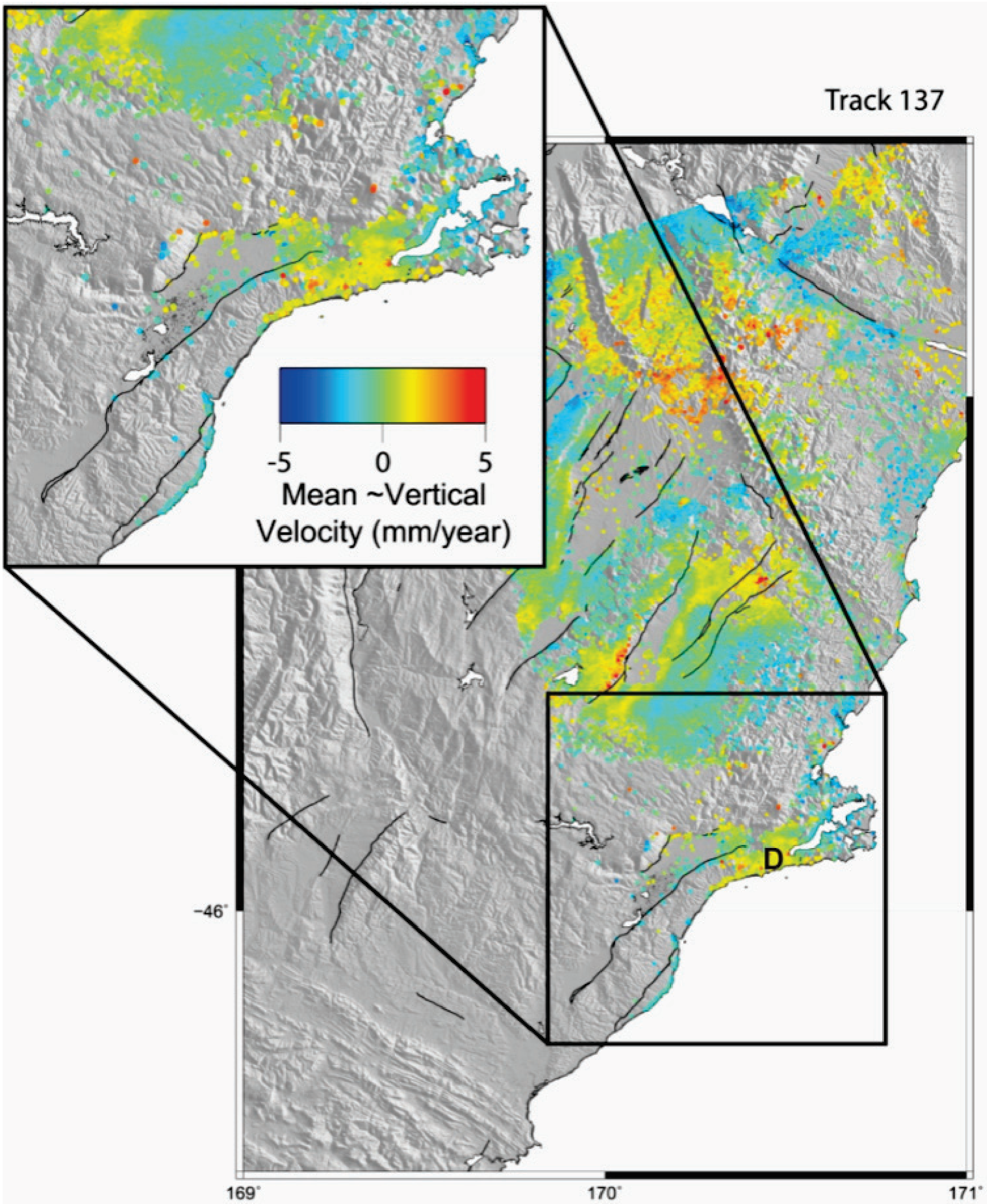


Figure 1.7.3 Velocity map of land movements from InSAR data for Track 137. D, Dunedin City.

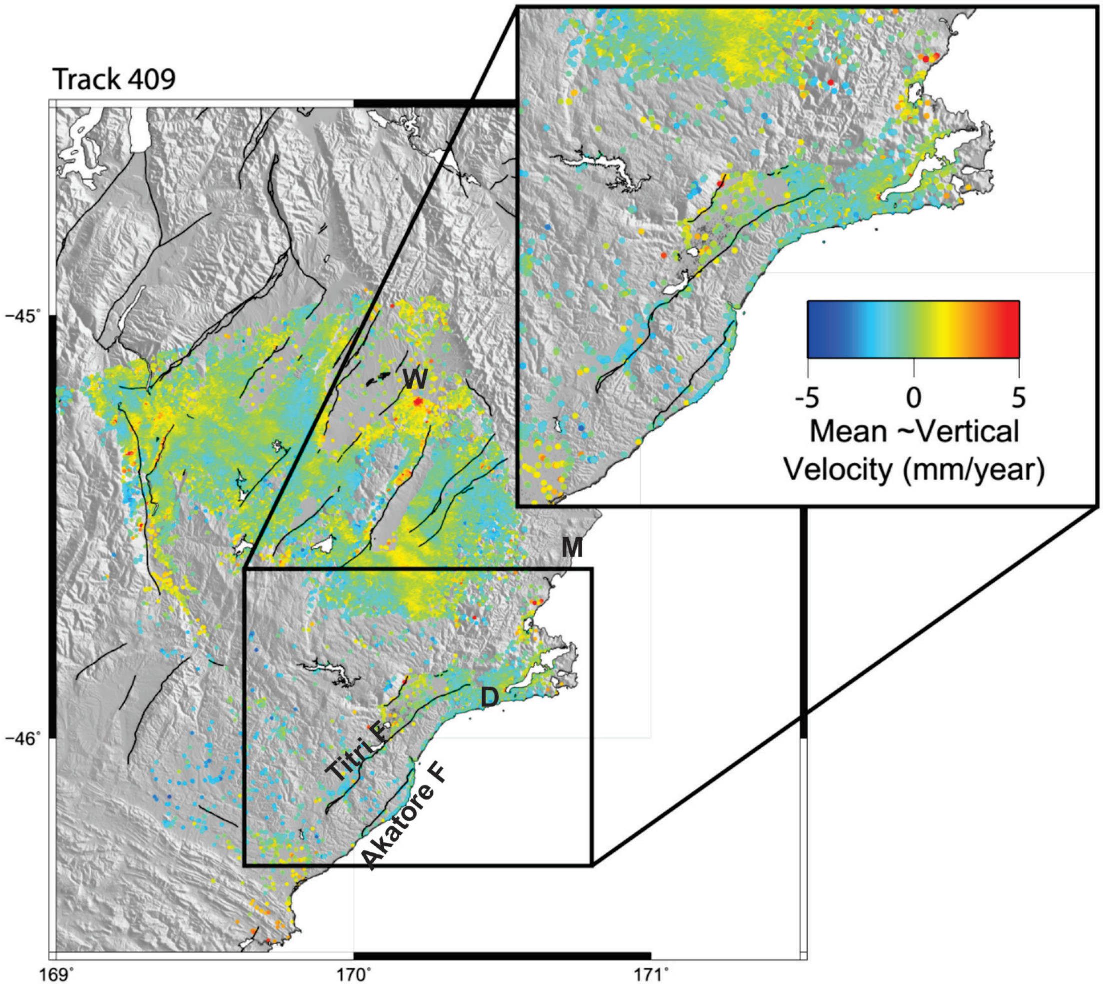


Figure 1.7.4 Velocity map of land movements from InSAR data for Track 409 that also includes the area around the Titri and Akatore Faults. W, Waipiata, D, Dunedin, M, Moeraki.

List of outputs

- 280 Envisat interferograms (dated 2003 to 2010) processed.
- INSAR surface deformation maps of the wider Dunedin City area produced.

1.8 Research Aim: Fault Sources

Title: Earthquake source characterisation from integration of surface and subsurface tectonic structure and crustal deformation

Budget: $18,790

Research Aim achieved? Yes

Discuss

Research Aim description: Assessment of active tectonic structures and their potential earthquake magnitudes in Dunedin city through integration of results: With new data and analysis from Research Aims 1.1 to 1.5 we will refine the active tectonic structure of the Dunedin area and assess the likelihood that the suspected lineaments are active structures. We aim to define the location, length and width of active structures. These fault parameters which will help assessing the earthquake magnitude associated with the potentially active faults. Assessment of deformation rates associated with identified active tectonic structures: We aim to convert geodetic, INSAR and seismicity rates from existing data and newly recorded data (Research Aims 1.4, 1.6 and 1.7) into "expected" rates for ground rupturing earthquakes using well-established seismological relationships. Quantification of uncertainties in the rates will be essential due to the large uncertainties in the low geodetic strain and seismicity rates in east Otago. We will also evaluate the implied earthquake rates according to criteria such as the estimated earthquake rates on faults in the surrounding region (e.g. Akatore, Green Island and Titri Faults), and whether the fault-based earthquake rates are consistent with the magnitude-frequency distribution of regional seismicity rates.

Results

Definition of active fault in the wider Dunedin area and age of the current tectonic regime

In this study we introduce a new definition of an active fault as "a fault that shows evidence of surface rupture or ground deformation during the current tectonic regime". The current tectonic regime refers to the length of time that the present state of Earth's crustal forces (direction and magnitude of stress) and consequent deformation style (fault type, fault activity rate, seismicity rates) have been operating in particular region. An underlying presumption is that the tectonic characteristics have remained unchanged over that period. Therefore, a fault that has moved at some time during the current tectonic regime is assumed to be capable of moving in the near future, even if it is presently quiet (Muir-Wood and Mallard 1992). This concept is used in low seismicity areas elsewhere in the world (Crone et al. 1997, Clark et al. 2012), and we consider it highly applicable to the Otago region. This definition is different to the one currently used in the New Zealand active fault database, namely a fault that has ruptured in the last 125,000 years (Langridge et al., 2016), and which has been the basis for determining which faults are incorporated in the National Seismic Hazard Model (NSHM; Stirling et al. 2012). This new approach allows us to better represent the distribution and activity of faults in low seismicity regions like Otago.

In the wider Dunedin area, the current tectonic regime has produced overall contraction, accommodated by reverse faulting, and at least some reversals of normal faults formed during a previous extensional tectonic regime. Although the current plate boundary initiated about 23 million years ago (Ma; King 2000), it is difficult to determine exactly when the current tectonic regime began in the Dunedin area. Some uplift and erosion had occurred prior to or during

episodes of basaltic volcanism at various times between ~23 Ma and ~10 Ma (Coombs et al. 2008). Other important considerations are that subduction at the southwest end of New Zealand began at ~10 Ma, and relative plate movement had become increasingly convergent by ~5 Ma (King 2000). As a result of these uncertainties we have selected three options for the start of Dunedin's current tectonic regime: 10 Ma, 5 Ma, and 2 Ma (youngest possible option).

Active tectonic structure around Dunedin and fault source model

Active faults are modelled as earthquake sources (hereafter called fault sources) for probabilistic seismic hazard assessment (e.g., Stirling et al. 2012). In the Dunedin area, fault sources included in the current NSHM are the Akatore, Billys Ridge and Hyde faults (Figure 1.8.1). Langridge et al. (2016) updated the active fault mapping in the area from previous data compilations (Bishop and Turnbull 1996; Turnbull 2000; Forsyth 2001; Heron 2014) and included the Maungatua and Titri faults as active (Figure 1.8.1).

In our study, based on the evaluations described in Research Aims 1.1, 1.2, 1.3, 1.4 and 1.5, we include many other faults that have moved during the current tectonic regime, such as Waitahuna Heights, Waitahuna Heights 2, North Taieri, Silver Stream-Merton, Kaikorai-Green Island, Flat Stream-Glenpark, Dunback, Murphys Creek, Hyde South-The Twins, Waihemo, Tuapeka, and Takapu faults (Figure 1.8.1). With respect to the specific investigation targets of the KWL and OHL lineaments, we identify a potentially active fault source (Kaikorai Fault) in the SW sector of the KWL, but not on the NE sector (see Research Aim 1.1). Since we have not found conclusive evidence for or against a potentially active fault along the OHL (see Research Aim 1.2), it is not included as a fault source.

Anticipated size and frequency of earthquakes from fault sources near Dunedin

The parameters that characterize the seismic potential of a fault source are: 1) the size of earthquake the fault could produce (magnitude - Mw); and 2) how often, on average, the fault ruptures (recurrence interval - RI). These parameters are ideally obtained from paleoseismic studies involving exploratory excavation and dating of fault-offset geological deposits. Parameters can also be obtained using empirical relationships/equation that use the fault length and the fault activity rate (or fault slip rate) as applied in the 2010 version of the NSHM (Stirling et al. 2012).

Paleoseismic data is only available for the Titri and the Akatore faults (Appendix 2; Taylor-Silva 2017; Barrell et al. 2018). The parameters for the other fault sources have been estimated using a variety of alternative approaches. One option uses geological data from Research Aim 1.1, assuming the deformation of the schist basement erosion surface across a fault started at the initiation of the current tectonic regime. Another option uses a combination of paleoseismic data for the Titri and Akatore faults and the preliminary geodetic deformation rate from Research Aims 1.6 and 1.7 for the rest of the faults (see more in Research Aim 1.9). To obtain Mw for all fault sources we used the fault length method (Stirling et al., 2012). We have considered options whereby all the sources defined in Figure 1.8.1 rupture independently, as well as options where various combinations of the sources could sometimes rupture together (i.e. with longer ruptures; see more detail in Research Aim 1.9).

Estimated earthquake magnitudes for fault sources in the Dunedin area range from Mw 6.7 to 7.7 and calculated RIs from 5000 years to 16 million years (my); values for each fault source are listed in Appendix 2. Larger Mw values are estimated for fault sources with longer rupture lengths. Our calculations produce large uncertainties in the RIs, with maximums of 35,000 to 1 million years estimated for the Kaikorai-Green Island Fault as an example. For the faults that are currently known to be active (Akatore and Titri) we obtained RIs of >5000 years, which are

slightly different to those obtained from field data. This is because we derive RIs from slip rate and fault length (following the NSHM methodology), rather than the timing between paleoearthquakes, even though we use slip rate derived from these data. For the purpose of this study, we accept these differences, but acknowledge that future efforts will need to be focused on resolving this discrepancy.

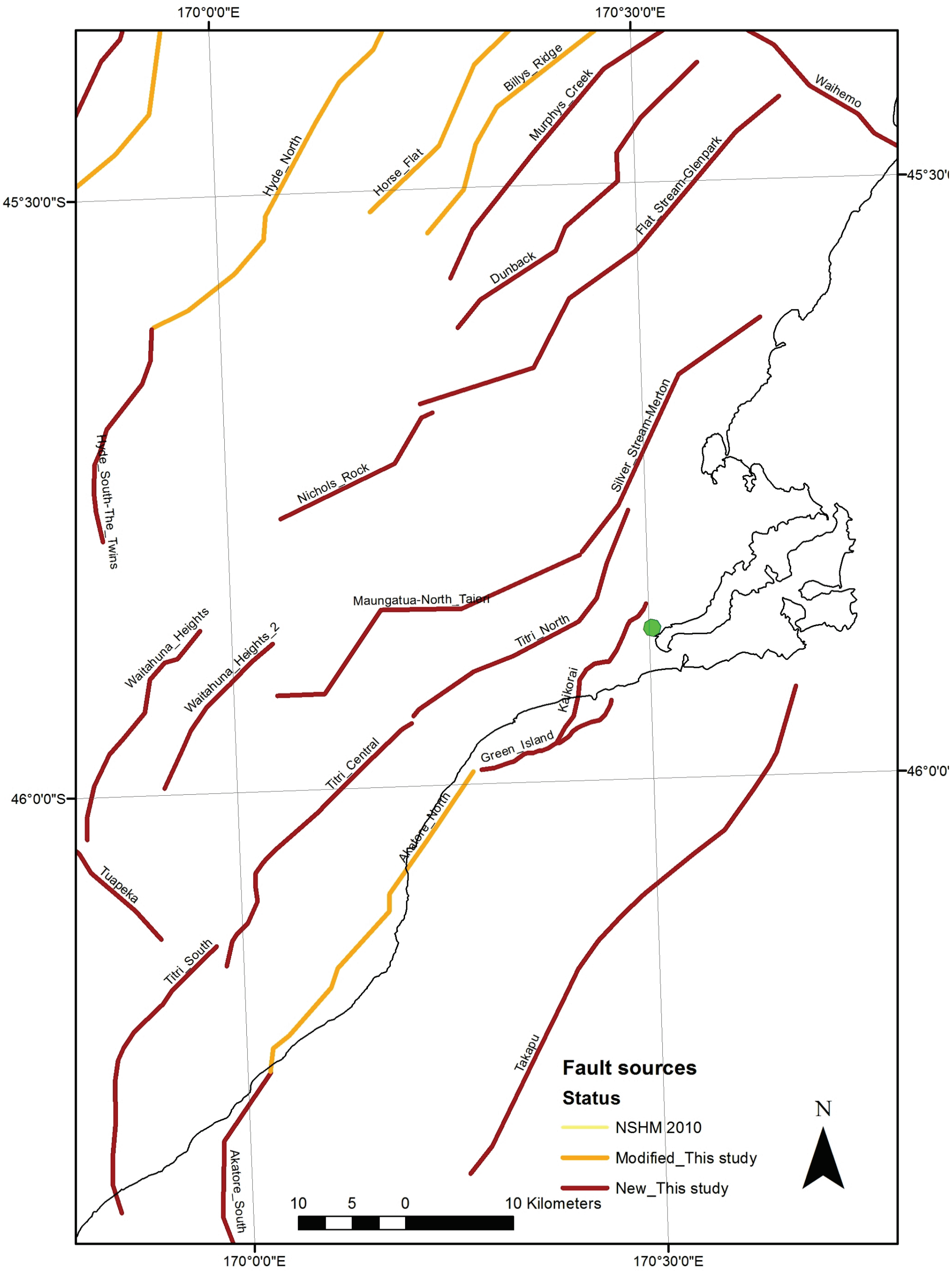


Figure 1.8.1 Updated surface traces for fault sources in the Dunedin region. Orange lines: fault sources modified from the 2010 NSHM. Red lines: new fault sources (not in the current NHSM). The green reference point is the Octagon in Dunedin city centre.

List of outputs

- New fault sources defined for the wider Dunedin area.

1.9 Research Aim: Seismic Hazard assessment and shaking scenarios

Title: Update of Probabilistic Seismic Hazard Assessment of Dunedin City

Budget: $18,000

Research Aim achieved? Yes

Research Aim description: Updated seismic hazard estimates for Dunedin city will be produced from this project. We will incorporate new fault sources into the national seismic hazard model and calculate the expected ground motions for a range of return periods (e.g. 500 and 2500 years) for representative sites in Dunedin. The new hazard estimates will then be compared to the existing hazard estimates for the city (Stirling et al. 2012) to assess the impact of the new fault sources. Scenario earthquake motions will also be developed for the new sources.

Results

Addressing fault source uncertainties for seismic hazard assessment: a logic tree approach

In seismic hazard assessment, it is important to account for the uncertainty in our understanding of the way faults behave. For that purpose, we evaluate and integrate diverse types of fault behaviour into the hazard calculation through a logic tree method (Figure 1.9.1). A logic tree allows for different options (or models) of fault behaviour to be defined; models are then weighted based on expert opinions of researchers. The hazard calculations are then integrated into a final result with contributions from each model based on their weights. In Appendix 3, we describe the methods used in this study to evaluate fault behaviours and the 16 models that were created for the logic tree.

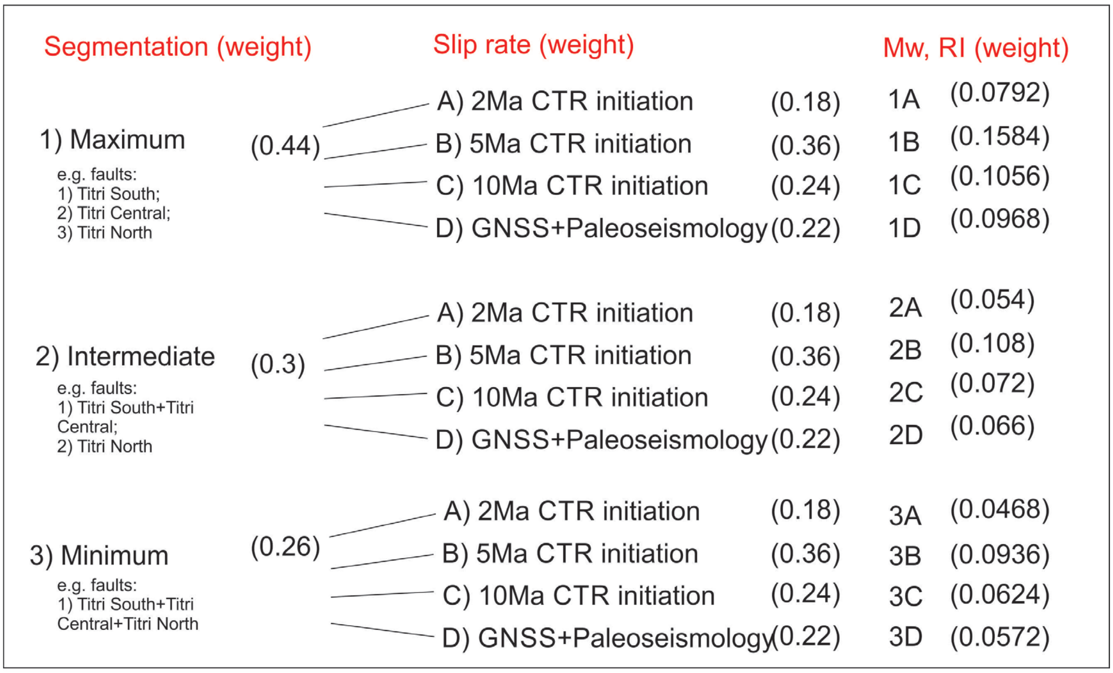


Figure 1.9.1 Logic tree for fault source models described in the text. Numbers in parenthesis are the weights assigned to each model or option. Appendix 2 contains a list of fault sources in each segmentation model, and how segments of long fault sources have been merged in models 2 and 3.

Seismic hazard assessment in Dunedin city

We have calculated seismic hazard curves using the Openquake hazards assessment software (https://storage.globalquakemodel.org/openquake/about/) and the new fault source model for a site in the centre of Dunedin (The Octagon). We compare those results with the hazard curve from the 2010 version of the NSHM (Stirling et al. 2012). The hazard curve in Figure 1.9.2 shows the probability of exceedance in 50 years (Y axis) of a given level of strong ground shaking (in this case expressed as peak ground acceleration, PGA, X axis, in units of g, or the Earth's gravity). For example, for the mean curve (black line) a PGA of 1 has a 0.06 probability of exceedance in the next 50 years (Figure 1.9.1) To be able to compare our results with the 2010 NSHM results for the same site we have kept all other variables the same (i.e., background seismicity, ground motion prediction equation, etc.).

The upper diagram of Figure 1.9.1 shows the hazard results using the different fault source models (colour lines) and their weighted mean (black line). The bottom diagram shows the comparison of our results with the 2010 NSHM curve for the same site. The 2010 NSHM curve is very similar to the weighted mean from this study at low ground shaking levels as these are dominated by the background seismicity (i.e., small to moderate earthquakes that occur randomly in the area) that is the same in all models. There is a slight difference in the higher ground shaking levels, with the new results predicting slightly larger PGAs for the same low probabilities. This is because we allow for longer fault sources to rupture (segmentation model 2 and 3). However, in general that difference is small because in the 2010 NSHM the north end of the Akatore Fault was close to Dunedin and was assigned a high slip rate of ~1.3 mm/yr (Stirling et al., 2012). This slip rate is considerably higher than the 0.4 mm/year estimated for the fault from recent paleoseismic work (Taylor-Sylva, 2017), and higher than any of the modelled faults assumed to lie close to the Octagon in this study (even for the maximum slip rates in Model 1A; see Appendix 2). In fact, our findings show that the summed contribution to hazard at the Octagon from the modelled faults in this study is equal to the contribution of the Akatore Fault alone in the 2010 NSHM. The end result is that the hazard estimates for our study are similar to the 2010 NSHM, despite our study having a more sophisticated analysis of the fault sources around Dunedin (e.g., the 2010 NSHM didn't have fault source segment options in the Dunedin area). Ideally as more paleoseismic and geodetic data are obtained, the hazard curves can be further refined.

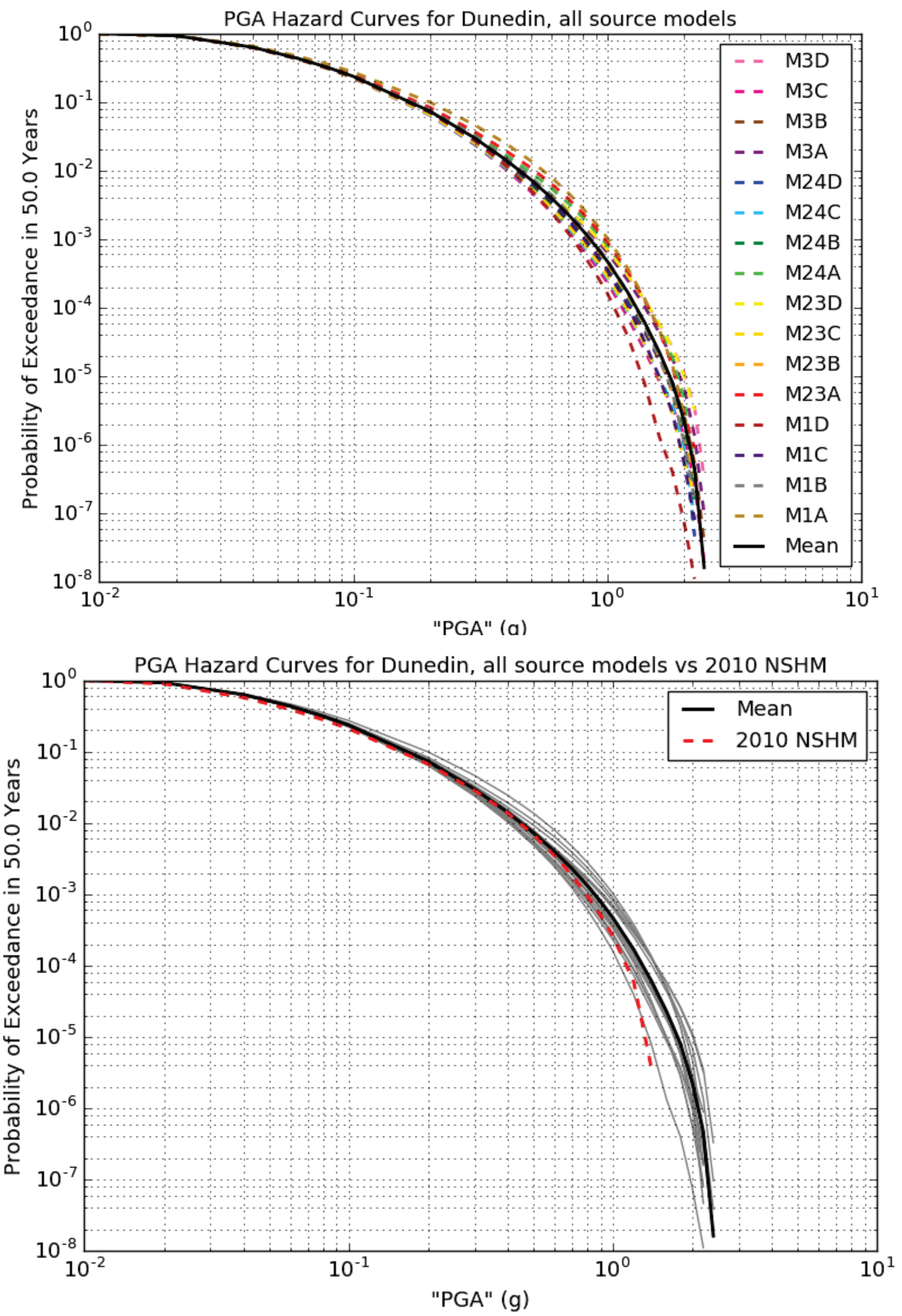


Figure 1.9.2 Seismic hazard curve for the Octagon site. Upper) hazard curves for the 16 fault source models described in the text (coloured lines) and their weighted mean (black line). See Figure 1.9.1 for the model names (e.g., M1A is for segmentation model 1 and slip rate model A). Lower) hazard curves for the 16 fault source models described in the text models (grey lines), weighted mean from th3 16 models (black line), and the 2010 NSHM curve (dashed red line).

Another important outcome from this study is that, while we have addressed the uncertainties in fault rupture lengths by allowing that two or three segments rupture together, the differences in the hazard curves from different segmentation models are small. This is because the slip rate budget used in this study is so low that it translates to very long RIs for the faults regardless of fault rupture model. Differences between the models are therefore only seen at the lowest probabilities, where the hazard curves are influenced by the large Mws of Models 2 and 3, and consequently lie above the 2010 NSHM hazard curve.

Rupture scenarios for faults in and close to Dunedin city: what shaking intensities are to be expected?

To better understand the possible shaking levels in Dunedin if nearby faults were to rupture, we have selected nine scenarios and calculated Modified Mercalli Intensities (MMIs) using ShakeMapNZ (Horspool et al., 2015). ShakeMapNZ predicts the levels of shaking that a certain fault may produce when it ruptures (see details for methods in Appendix 4). The scenarios (Table 1.9.1) represent possible ruptures of the Kaikorai-Green Island, Akatore and Titri Faults using the different segmentation models described in Research Aim 1.8. We also calculate the MMIs for the Akatore Fault as modelled in the 2010 NSHM (2010-Akatore in Table 1.9.1). For each scenario we have assumed two end-member positions for the earthquake hypocentre (or rupture starting point along the fault), the closest and farthest point on the fault source to the city. The hypocentre location is typically the zone of maximum energy release during the earthquake. The results are show on Table 1.9.1. To put the MMI estimates into a likelihood context, we also provide the rupture recurrence interval. Table 1.9.1 shows that MMI intensities ranging from 6 to 9 are plausible with the scenarios presented in this study. Definitions for MMI 6 to 9 are provided in Appendix 5.

Table 1.9.1 Modified Mercalli Intensity in Dunedin city for different fault rupture scenarios in this study and for the Akatore Fault from the 2010 NSHM (2010_Akatore).

Scenario: Fault Name	Mw (segmentation model)	MMI	Recurrence Interval (years)
SCN1: Kaikorai_GreenIsland	6.9 (1)	8-9	31500-1,150,000
SCN2: Akatore_North	7.1 (1)	6-8	6150-86,200
SCN3: Kaikorai_GreenIsland + Akatore_North	7.4 (2)	8-9	14,000-250,000
SCN4: Kaikorai_GreenIsland + Akatore_North + Akatore South	7.6 (3)	8-9	21,300-360,000
SCN5: Titri_North	7.0 (1)	7-8	5700-200,000
SCN6: Titri_Central	7.0 (1)	6-7	4900-24,600
SCN7: Titri_North + Titri_Central	7.4 (2)	8	12,700-63,450
SCN8: Titri_North + Titri_Central + Titri_South	7.7 (3)	7-8	18,350-91,800
SCN9: 2010_Akatore	7.4	7-8	3500

From the nine scenarios, perhaps of more relevance to Dunedin seismic hazard are the segments of the Akatore and Titri faults that have evidence for geologically recent rupture (Akatore North and Titri Central), based on paleoseismic studies (Taylor-Sylva, 2017 and Barrell et al., in prep). Rupture of individual segments of Akatore and Titri faults (SCN2, SCN5 and SCN6; Table 1.9.1) could produce MMIs larger than 6. Depending on how close the earthquake hypocentre is, some parts of Dunedin may experience MMI 8 for scenarios with rupture of the Titri North fault (SCN5). In such scenarios damage to unreinforced masonry building will occur with some partial collapses for cases of MMI8. Liquefaction and landsliding will also be present, and significant in areas of high susceptibility for MMI8 cases. The MMI values obtained for the Akatore and Titri fault sources as defined here are similar to those obtained using the Akatore Fault from the 2010 NSHM (Stirling et al. 2012) (SCN9; Table 1.9.1). The recurrence interval for Akatore and Titri Fault scenarios (larger than 3000 years from paleosesimic data on the Akatore Fault; Taylor-Sylva 2017) suggest that this level of shaking will influence shaking levels used to design critical facilities that need to be functional after an event.

Somewhat higher MMI (MM8 to 9) values are obtained for those scenarios with involvement of the Kaikorai-Green Island Fault (SCN1, SCN3 and SCN4) because of the proximity of the Kaikorai Fault to the city. However, this scenario has an extremely low probability of occurrence based on the RI values obtained in this study.

The shaking scenarios for the Dunedin city caused by rupture of nearby faults could be, at least, of the same level as that experienced in Christchurch city during the Mw 7.1 2010 Darfield Earthquake. In that earthquake, MM6-7 was observed in Christchurch city (Wood et al., 2012), ~30 km away from the causative Greendale fault (Quigley et al., 2012). The recurrence interval of the Greendale Fault that ruptured in 2010 has been estimated at ~36,000 years (Hornblow et al.,2014). In contrast to Christchurch prior to 2010, Dunedin city has only experienced one lightly damaging earthquake in the 1970s. However, the city has two large active faults (Akatore and Titri) at closer distance to the city (<20 km) than the Greendale Fault is to Christchurch. We have also highlighted the possibility that another active fault lies at the western edge of the city, the Kaikorai fault (although less active or perhaps quiescent). We have been unable to confirm whether the north-eastern alignment of Otago Harbour is related to the presence of an active fault.

1.10 Research Aim: Integration, communications and stakeholder engagement

Title: Integration of results, stakeholder engagement and science communication

Budget: $55,380

Research Aim achieved? Yes

Discuss

Research Aim description: The integration of knowledge during the project will be happening at different stages, through a series of meetings including key stakeholders. A project start-up meeting will aim to use the combined knowledge to design data acquisition campaigns for the various techniques. A second meeting will be held after preliminary analysis of the data to discuss results, and integration meetings to define integrated results prior to report writing. Individual team meetings will be held as required during the project duration. A science report will be produced with the main results from this project. We will also communicate our results to the national scientific community through organisation of a conference session during the New Zealand Geoscience Society Annual Conference.

Meetings for Integration of results

The multidisciplinary and multi-institutional approach of this project required a clear and strategic plan for results dissemination among team members and integration of results. This was achieved through a series of project meetings with the whole team (2) and meetings with selected members (8). Most meetings were held in Dunedin. Quarterly reports were used also as a means to disseminate research updates between team members.

Communicating of results to the national scientific community and stakeholders

We communicated with the scientific community through presentations of results and project plans at national or local conferences:

- 2015 Geoscience Society of New Zealand Annual Meeting (Villamor et al., 2015; Holt and Gorman, 2015). Discussions held with researchers from Waikato and Auckland Universities and geologists from Nelson to develop the initiative in other cities.
- 2016 Geoscience Society of New Zealand Annual Meeting (Barrell, 2016; Villamor's presentation was cancelled because of the Kaikoura Earthquake response).
- 2018 Geoscience Society of New Zealand Annual Meeting (upcoming). We will present the final results.
- Catalyst Fund Project – Faults and Cities: Utilising Geophysics to Support Investigations of Active Faults in Urban Centres: GNS Science Workshop April 2017 (attended by representatives from University of Canterbury; University of Auckland; University of Otago; NIWA; Southern Geophysical; Golder Associates; Leibniz Institute of Applied Geophysics, Germany; University of Wisconsin, USA; University of Calgary, Canada).

Data or results have been part of, or will be used by, University of Otago undergraduate, graduate and postgraduate programmes:

- Research Aim 1.2: Andrew Holt, 2017 MSc thesis (completed)
- Research Aim 1.3: The onshore seismic lines were collected as part of GEOL261/361 field school

- Research Aim 1.3: Catherine Sangster MSc thesis (on-going)
- Research Aim 1.3: The Kaikorai seismic line has provided some data for Anna Kowal's PhD study (QuakeCoRE PhD scholarship, 2018-20) to develop 3D shear wave velocity models for ground motion simulations for Dunedin and Mosgiel.
- Research Aim 1.4: Research Aim Micro-earthquake database shared with Victoria University and University of Otago
- Research Aim 1.5: Data will be used by MSc study by Tim Lutter at the University of Otago on gravity modelling of the Dunedin volcano

The philosophy and partial results from this study have been presented to, or used by, stakeholders including: Earthquake Commission, Otago Regional Council, Dunedin City Council, Geonet, Dunedin Rotary Club, University Club, Kings High School Curious Minds Project, Bayfield High School Curious Minds Project, Mosgiel and Dunedin U3A clubs, Curious Minds “What lies beneath” Project (Otago Regional Council, Otago University, NZ International Science Festival), Labour MPs for South Dunedin.

Partial results have been featured in The Press, Christchurch (interviewing Villamor, Stirling and Gorman) and the Otago Daily Times (interviewing Local Dunedin MP).

List of outputs

- Quarterly and final report.

2.0 CONCLUSIONS AND RECOMMENDATIONS

To assess the location of faults, their activity rate and their contribution to seismic hazard, we used a multidisciplinary approach. The disciplines used (see Research Aims 1.1 to 1.8) were:

- Analysis of rock and fault exposures, and mapping of landscapes surfaces (Research Aim 1.1) has helped us identify and locate 21 potentially active faults onshore, most of which are currently inactive or dormant (see below).
- Imaging of the layers under the sea (research Aim 1.2) and the ground surface (Research Aim 1.3) with geophysical techniques has helped: map the location the Green Island Fault offshore; confirm the presence of the Takapu Fault offshore; and confirm that the Akatore fault does not extend onshore into the Kaikorai Valley.
- Measures of the Earth's gravity (Research 1.4) discriminated whether some areas may have subsided as a result of long term fault displacements. Gravity measurements in the city show absence of big steps of the basement rocks, which suggests that there are not major faults under the city.
- Seismographs were installed in order to identify subtle signals of fault activity at depth (Research Aim 1.5). Seismographs did not detect any movement under Dunedin city.
- Measurements of ground movement with GPS instruments (Research Aim 1.6) and analysis of satellite images (Research Aim 1.7) provided a preliminary value of 1 mm/yr contraction across the wider Dunedin region.

Results from Research Aims 1.1 to 1.8 were used to:

- Define fault sources (Research Aim 1.8) in Dunedin city and wider region around the city. In this study we adopted a different definition of 'active fault' than that traditionally used in New Zealand. Instead of defining active fault as the fault that has ruptured in the last 125,000 years, we define it as the fault that has ruptured within the time that the current Earth's forces have been constant in this region (or current tectonic regime). This definition suits areas of low seismicity as faults in these regions can be quiescent for periods of more than 125,000 years and then become active again.
- Research Aims 1.1, 1.2, 1.3, 1.4, 1.5 and 1.6 not only helped to indicate the absence of major faults under Dunedin city (see below), but also helped define expected earthquake magnitudes (Mw) for all faults.
- Research Aims Fault 1.1, 1.6 and 1.7 helped asses fault rupture recurrence intervals (RI). With that information, a probabilistic seismic hazard assessment centred on the Octagon, but relevant to the city generally, was undertaken, as well as strong ground shaking scenarios estimations for future rupture of faults close to Dunedin city.

The key findings of this study in terms of active fault locations are:

- The Akatore Fault does not extend into the city.
- The Titri Fault extends northwards and closer to the city than previously mapped, but it has buckled rather than broken the ground surface there.
- A newly mapped and possibly active fault, the Kaikorai Fault, lies in the western part of the city. This fault may rupture together with the Green Island Fault offshore.
- The south part of the KWL is related to the Kaikorai Fault but the central and northern parts of the KWL do not seem to be related to hidden faults.
- Our study was non-conclusive on the presence of active faults along the Otago Harbour, the OHL.

- While the Akatore and Titri faults seem to be in an active period (from studies parallel to this one), the Kaikorai is currently either inactive or in a dormant phase.

The key findings of this study in terms of the seismic hazard to Dunedin city are:

- Earthquake parameters for fault sources for the Dunedin area range from Mw 6.7 to 7.7 and RIs of 5000 years to 16 Ma. These large ranges are a consequence of the treatment of uncertainties in our knowledge on fault rupture length and fault recurrence interval.
- This study does not substantially change the levels of hazards calculated for Dunedin city. Part of the reason for this is that the new faults defined using the current tectonic regime criterion have been assigned very low levels of activity (quiet time).
- Improved estimates of the activity of the Akatore and Titri faults (from recent studies and used here), sum up to the same value that was previously assigned to the Akatore Fault. Therefore, our results are similar to those presented by 2010 NSHM which in turns informs the New Zealand Building Code.
- We have also assessed possible strong shaking scenarios in Dunedin from rupture of some faults. Although these values have large uncertainties, rupture of on the nearby faults could result in ground shaking of MM6, and perhaps to MM8, in some parts of Dunedin city. Ground shaking at MM6-8 will likely result in damage to unreinforced masonry buildings and could produce landslides and liquefaction in some areas. It is important to remember however, that the likelihoods for these rupture scenarios are low (RIs >3000 years), but not necessarily lower than those of the faults involved in the Canterbury earthquake sequence.

3.0 RECOMMENDATIONS OF FUTURE WORK

A better understanding of the presence and levels of active faults beneath, or close to, New Zealand cities is essential for appropriate and effective preparation and implementation of emergency response, land use planning and risk management. In low seismicity areas, presence of active faults and their level of activity are difficult to assess. Multidisciplinary projects like this help arrive to conclusions that one single technique will not be able to reach. However, we have only scratched the surface of the understanding of fault activity in Dunedin and wider region, as more data and analysis are required to reduce the uncertainty on our knowledge.

Specific recommendations for future studies in the Dunedin region include:

- Measurement, analysis and maintenance of the GNSS sites around Dunedin and analysis of new generation satellite images, as they become available, to refine deformation rates across Dunedin;
- Increase of the coverage of offshore and onshore geophysical studies to confirm presence or absence of active faults, but also to characterise the properties of sediments under the city to evaluate potential amplification of seismic waves;
- Further paleoseismic studies to better understand fault behaviour (active versus quiet periods);
- Incorporation of different fault source characterisation methods to better address our lack of understanding of how faults behave in low seismicity areas.

With this study, we have advanced the knowledge, tested techniques that have proven useful for finding faults under cities, and set a base line for Dunedin city that should be revisited as new data is available. Ideally, multi-discipline, multi-agency (researchers, regional and local authorities, infrastructure owners, etc.) and multi-year (5+) programs should be established for each New Zealand City (e.g., IOF in Wellington, https://www.gns.cri.nz/Home/IOF/It-s-Our-Fault; and DEVORA in Auckland, http://www.devora.org.nz/) to slowly build our knowledge around potential active faults close to our cities.

4.0 ACKNOWLEDGMENTS

EQC funded the SUTT cGNSS station. Lara Bland and her team installed the SUTT cGNSS station despite being busy with event response. Otago Regional Council endorsed the proposal to obtain funds for this study. University of Otago and GNS Science contributed with in-kind funds. University of Otago's GEOL261/361 field school students helped with surveys for Research Aim 1.3.

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APPENDICES

A1.0 A DETAILED ACCOUNT OF THE RESULTS OF RESEARCH AIM 1.1

The work for Research Aim 1.1 comprised: (a) new fieldwork in proximity to suspected faults on the western side of the upper valley of the Water of Leith, between 6 and 9 km north of the Dunedin CBD, and; (b) a review and compilation of existing geological mapping, resulting in the preparation of a map of structural contours (or isolines of equal topographic elevation) on distinctive lithological boundaries within the geological stratigraphic succession, and tectonic interpretations of that information.

The geological work in this project has benefited from complementary effort from two other research projects, the 'Dunedin urban geology' task of the GNS Science core-funded "Minerals, Urban and Regional Geology" programme, and a GNS Science EQC-funded project "Earthquake hazard in Dunedin: paleoseismology of the Titri Fault (Project No 16/719)".

Leith Valley field investigations

The topography of the field area on the western side of the upper Leith Valley sector of the KWL is rough and rugged, on densely forested steep slopes. The terrain made the fieldwork quite challenging but the numerous waterfalls and steep slopes offered good, though very localised, rock exposure.

The field area was chosen because Benson's (1969) geological map (Fig. A1.1.1) shows two substantive northeast-striking faults transecting the area, spaced 600 m apart. Fieldwork has largely confirmed the validity of the geological outcrop pattern shown on Benson's (1969) map. Between the locations of Benson's two mapped faults is a sequence of Dunedin Volcanic Group (DVG) rocks (Fig A1.1.2) inclined to the southeast at an average dip about 60 degrees. The dip is considerably steeper than could be accounted for as a primary (depositional) attitude. Slickenside striations on fracture surfaces within the volcanic rock indicate oblique dextral (normal) movement (Fig. A1.1.2). No major faults were directly observed. The geological outcrop observations can be accounted for by a steeply-dipping package of strata, with dips shallowing off either side to the west and east. We find no necessity for the two faults mapped by Benson (1969) in in upper Leith Valley and suggest the geological units can be best explained by non-tectonic processes.

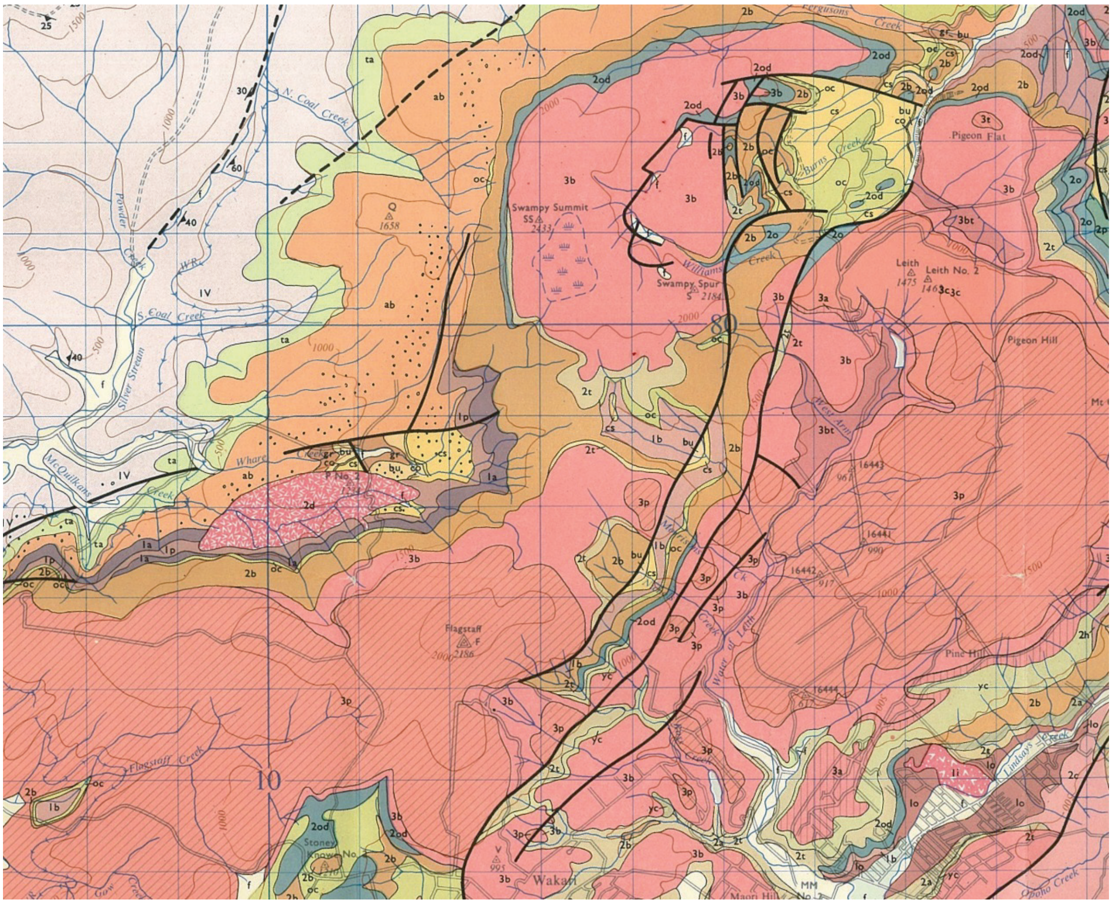

Figure A1.1.1 Extract of Benson’s (1969) geological map highlighting the two NE-striking faults on the western side of the Water of Leith catchment (black lines just right of centre). The northwestern one is shown as offsetting Burnside Mudstone (bu; Eocene-Oligocene marine unit) and Caversham Sandstone (cs; Early Miocene marine unit) up to the southeast against Middle to Late Miocene Dunedin Volcanic Group (DVG) strata (labelled 1, 2, 3, or yc, oc for different components). The southeastern fault is shown as having a relatively smaller throw, up to the southeast, where windows of DVG rock of the (older) 2nd Eruptive Phase (labelled 2) are depicted in fault contact with 3rd Eruptive Phase rocks (labelled 3). Between the two faults, the map depicts a package of volcanic rocks with a steep SE dip, judging from the map pattern, which has been confirmed by the new fieldwork reported here. The map pattern illustrates well the slight angular discordance that exists between the base of the DVG and the older strata, with DVG resting on progressively older strata to the west (Caversham Sandstone (cs), Burnside Mudstone (bu) and Abbotsford Formation (ab).

Figure A1.1.2 Upper photo - subvertical lithological contact between a grey basalt flow rock, a reddish ash layer, and a lighter coloured volcanic rock to right, in Morrisons Burn. Lower photo - West-dipping fractures in alkali basalt exposed in Morrisons Burn. Fracture surfaces have prominent NE-plunging striations pitching 45-80 degrees.

Structure contouring and tectonic interpretations

Much of the area around Dunedin city is underlain by lithologically and architecturally complex volcanic strata of Miocene age, which tend to mask the more uniform ('layer-cake') sedimentary succession below (within which tectonic structures are more readily definable). For that reason, some effort was made to examine the Late Cenozoic geological structure in areas to the north and west of the city, where remnants of the older strata, and in particular the paleoerosion surface (Waipounamu Erosion Surface or WES, aka Otago peneplain) at the interface between underlying schist basement rock and the overlying Late- Cretaceous-Cenozoic sedimentary succession, are extensively preserved. The rationale was that characterising the Late Cenozoic tectonic structure (faulting and folding) in a nearby area where it is better preserved/expressed, will provide useful context and guidance for identifying and interpreting suspected tectonic features closer to Dunedin.

The structure contouring, together with field observation and literature review, has been help identify faults around Dunedin that could potentially be active. The results of this work are illustrated on a map, illustrated here in three frames, Map 1 showing the full extent of the assessment area at 1:300,000 scale (Fig. A1.1.3), Map 2 at 1:150,00 scale (Fig. A1.1.4) focusing on the wider Dunedin area, and Map 3 (Fig. A1.1.5) focused on Dunedin.

There is a marked structural change either side of a line drawn northwest-southeast from Dunedin. This is highlighted on three cross sections with structural interpretations (Fig. A1.1.6). To the northeast of Dunedin, there are prominent NE-striking fault/fold blocks, on a 5-10 km spacing. A good example is the Flat Stream Fault (Maps 1 and 2, Figs. A1.14-1.1.5., and Fig. A1.1.7). To the southwest of Dunedin are some prominent northwesterly-downthrown faults (Waitahuna Heights, Titri and Akatore), plus a prominent structure downthrown to the southeast, or perhaps series of structures, the Maungatua-North Taieri-Merton faults. There are some prominent dome-like structures on the upthrown sides, notably Maungatua, the Silver Peaks and Lamb Hill. Along strike at the northeast end of the Titri Fault is a large, prominent anticline, defined in all stratigraphic units, coined the 'Titri Anticline' (Liggett, 1975). There is evidence for an at least locally steepened/sheared limb at Three Mile Hill Road, indicated by close-spaced contours southeast of the word 'Titri' in Fig. A1.1.5.

In the immediate area of Dunedin (Fig. A1.1.5), the contouring has identified several structural features. The largest in terms of amplitude, and with high confidence of its existence, is the Titri Anticline mentioned above. The next most significant feature is identified as the Kaikorai Fault, whose presence is most robustly indicated by a ~60-80 m difference in the elevation of the base of the DVG either side of Kaikorai valley, and is provisionally interpreted to be a northeast-striking fault upthrown to the southeast. Minor faulting close to the line of the fault was identified in bedrock by Barrell and Litchfield (2013), but it was not clear whether the faults are of tectonic or slope movement origin.

There is less certainty regarding the Blackhead Fault and Ravensbourne Fault (Fig. A1.1.5), both shown on Benson's map, because their recognition depends on the validity of Benson's differentiation of the 1st and 2nd eruptive phase rock units (dvg- 2 EP in Figs. A1.1.3-A1.1.5). Taking Benson's map at face value, there is an ~100 m downthrow to the southeast on both those faults. Qualms about the validity of the fault interpretation include whether the geological relationships may instead relate to paleotopography existing at the time of volcanic eruption, or possibly slope instability within the former volcanic edifice. Those two faults, if real, coincide approximately with the OHL (Fig. 1.0.1), but it is considered that from present information, their identification is too uncertain to warrant pursuing that interpretation any further.

Similarly, the recognition of two open synclinal folds, the Leith Syncline and Waitati Syncline also depends to some extent on the validity of Benson's eruptive phase mapping. However, we think there is more solidity to the identification of these folds, because they do lie along km-scale variations in strata dip, notably the southeastward dip of strata off the crest of the Titri Anticline, versus the generally horizontal overall disposition of the volcanic strata in proximity to Otago Harbour.

A particularly notable finding from the structure contouring is that the package of steeply dipping volcanic rock in Leith valley (the belt of closely-spaced contours between the axes of the Titri Anticline and Leith Syncline) does not persist along strike in either direction. This interpretation of a lack of continuity is strongly founded because the structure contours in that area are on the base of the DVG rocks, which is a geologically very distinctive horizon and is generally mappable with good accuracy. The belt of steeply dipping rocks can be no more than ~5 km long, and this means that it cannot be associated with an independent fault source structure, because such a structure would need to be much longer in order to have produced such profound near-surface deformation. Instead, it is tentatively interpreted to be subsidiary deformation over a blind back-fault splay associated with the Titri Anticline, as illustrated in Fig. A1.1.6, central cross-section. In that diagram, the package of steeply dipping volcanic rocks is identified as 'Nicols monocline'.

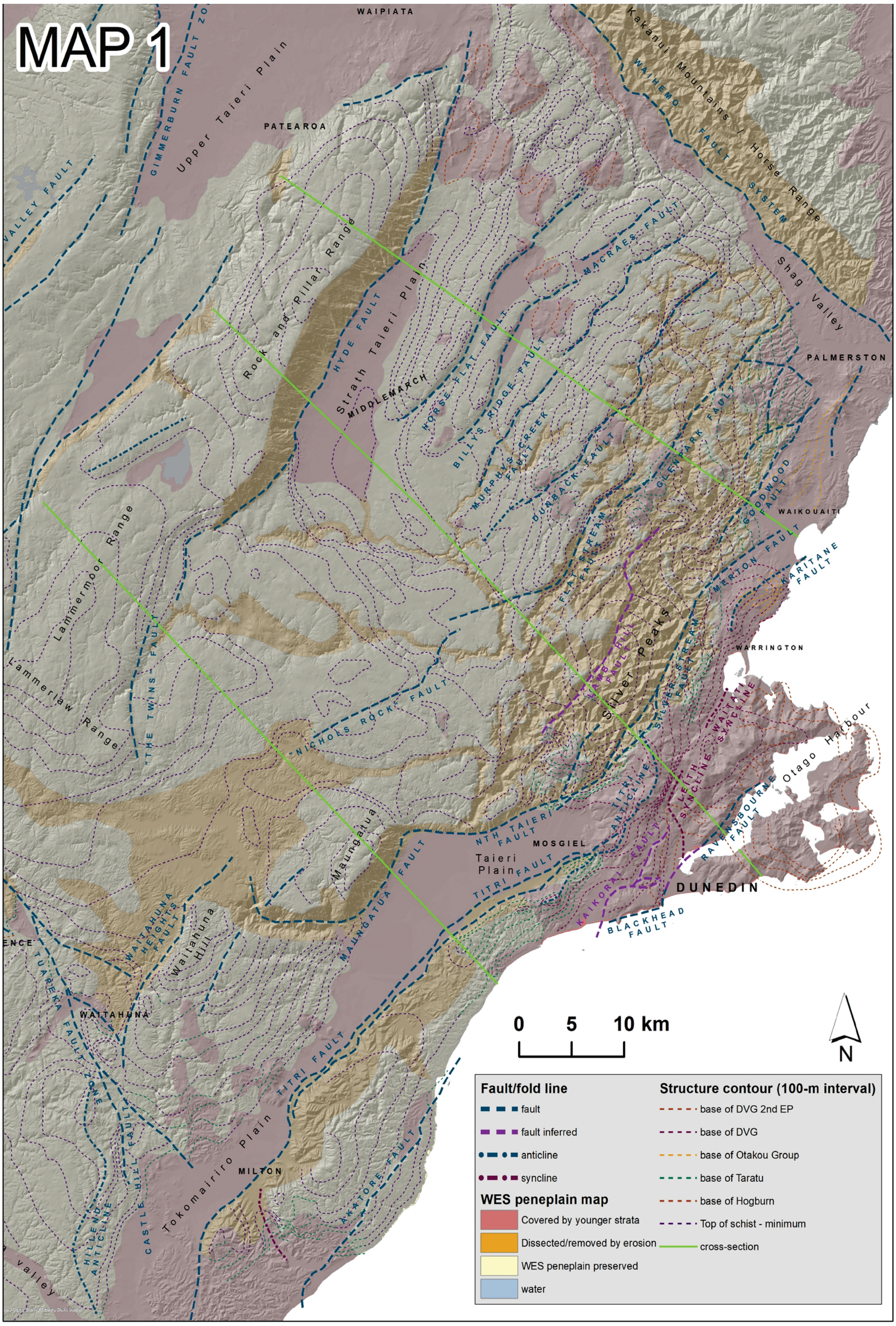

Figure A1.1.3 Structure contour map, showing structure data control points (where geological boundaries cross topographic contour lines), structural contours on different geological horizons, faults and interpreted fold axes. The underlying map is an interpretation of the extent of the Waipounamu Erosion Surface (WES). Also shown are the locations of cross-section lines (northeastern, central and southwestern; Fig. A1.1.7).

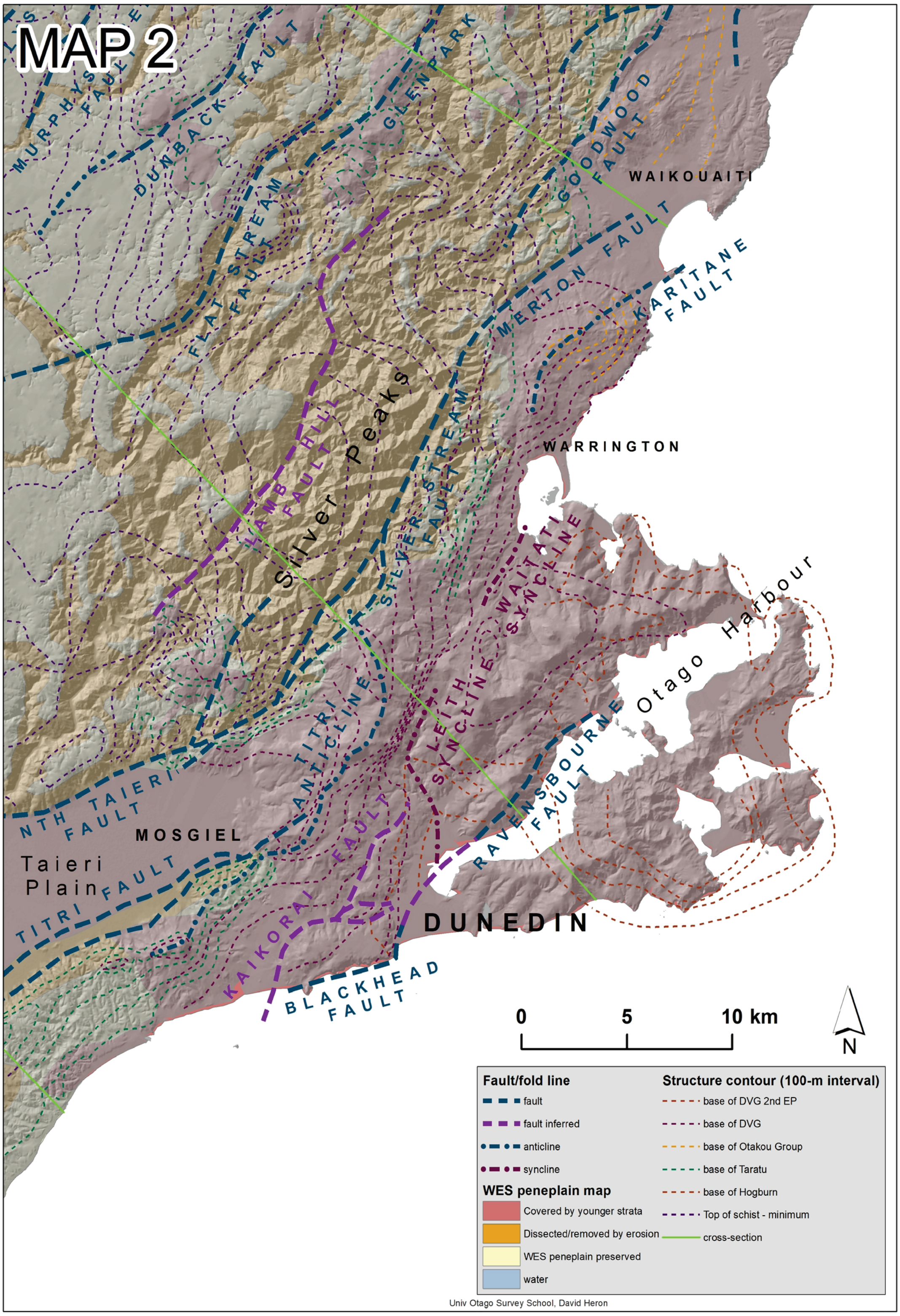

Figure A1.1.4 An enlargement of the structure contour map for the wider Dunedin area. Refer to Fig. A1.1.3 for description of map components.

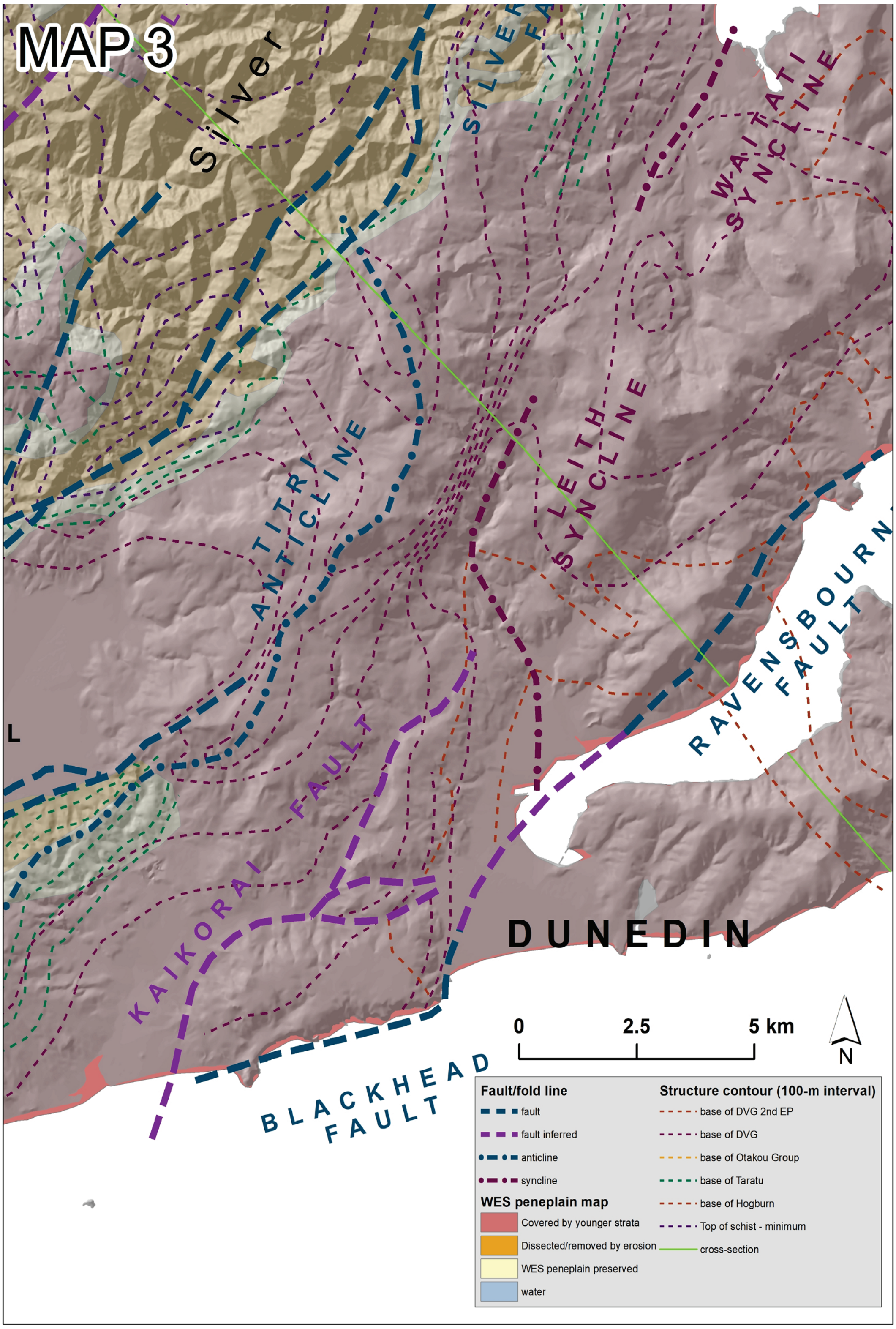

Figure A1.1.5 An enlargement of the structure contour map focusing on the Dunedin area. Refer to Fig. A1.1.3 for description of map components.

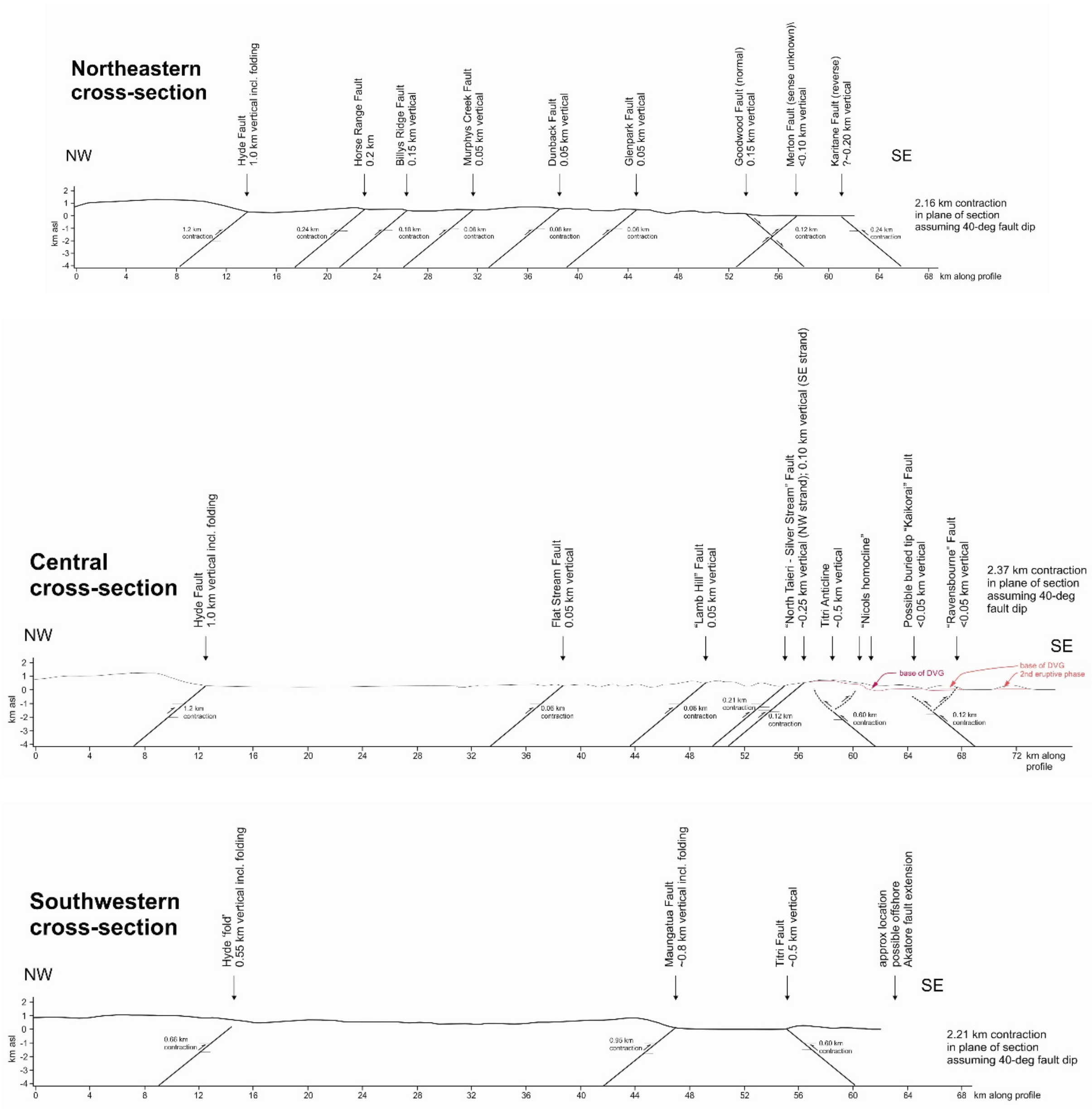

Figure A1.1.6 Cross-sections illustrating the structural interpretations, with section line locations shown in full on Fig. A1.1.3. A nominal 40 degree dip is applied to all faults, for the purpose of estimating tectonic shortening. Differing interpretations of dip angle may have been used in formulating the fault source model (Research Aim 1.8).

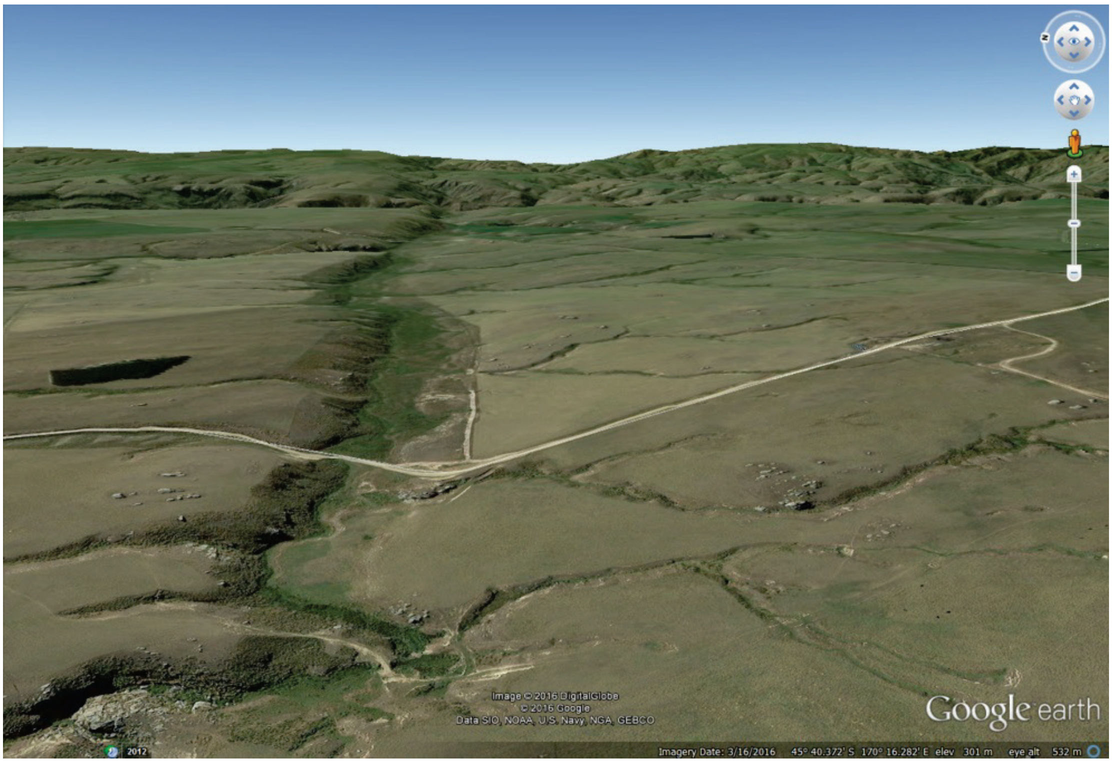

Figure A1.1.7 Google Earth image looking northeast along the Flat Stream Fault, close to its southwestern end. Barewood Road is in the foreground. The smooth land surface in the fore to middle ground is an exceptionally well-preserved remnant of the Waipounamu Erosion Surface (WES). The fault scarp displaces the WES here by ~10-20 m, up to the NW (left). Throw is greater along-strike in the distance, on the far side of the Taieri River. There, a ridge of hills within very dissected WES terrain is uplifted on the NW side of the fault by as much as ~150 m. The prominence of the fault escarpment is primarily a function of the ancient land surface (its fundamental character is at least as old as Miocene) developed on hard schist rock. There is no indication of whether or not there may have been any Quaternary movement.

What is the KWL?

Overall, we conclude that the KWL is not associated with a single geological structure, but rather is a linear coincidence of, in the northeast, synclinal troughs at the southeastern margin of Titri Anticline uplift, and in the southeast, the Kaikorai Fault block. The most important controlling structure is the Titri Fault and, where blind, its related anticline. Of added note is the similar but much smaller the Kaikorai Fault, to its southeast.

The combination of the contouring and the fieldwork in the upper Leith valley suggest that steep structure represents a local steepening on the southeastern limb of the Titri Anticline. The Titri Fault to the south undoubtedly has experienced Quaternary-age surface ruptures, but the geological relationships indicate that to the north, it becomes a blind fault underlying a large-scale anticline. Our preliminary interpretation is that the Leith and Waitati synclines are real structures, but mark the transition from tilted strata on the southeastern flank of the Titri Anticline to generally non-tilted strata associated with the main body of Dunedin Volcano. Thus we infer that they are essentially passive features that are not directly associated with an underlying fault.

Farther south along the KWL is the inferred Kaikorai Fault, upthrown to the southeast. The topographic elevation of that side of the fault may be a primary tectonic morphology, although we cannot discount it being at least partly due to differential erosion. Although it has a similar orientation and sense of throw to the Akatore Fault, there is good reason to regard them as similar, but separate, structures, as addressed in Research Aim 1.8. The Akatore Fault has experienced multiple Holocene ruptures, but it is clear from the lack of landform disruption that the Kaikorai Fault has not experienced Holocene rupture, nor does it show any direct evidence for Quaternary offsets. It is nonetheless identified as a potentially active fault. Thanks to the EQC project mentioned earlier, conclusive evidence has now been obtained that the Titri Fault has had multiple late Quaternary surface ruptures.

A2.0 MAGNITUDE (MW), SLIP RATE (SR) AND RECURRENCE INTERVAL (RI) FOR EACH FAULT SOURCE MODELLED IN THIS STUDY

MODEL	Fault-ID	FaultName	Mw	MODEL A		MODEL B		MODEL C		MODEL D	
				SR Ave	RI Ave	SR Ave	RI Ave	SR Ave	RI Ave	SR Ave	RI Ave
1	1	Hyde_North	7.4	0.68	5,604	0.27	14,009	0.14	28,019	0.019	204,162
	2	Hyde_South-The_Twins	6.8	0.25	5,909	0.10	14,774	0.05	29,547	0.007	215,298
	3	Horse_Flat	7.0	0.12	17,137	0.05	42,843	0.02	85,687	0.003	624,364
	4	Billys_Ridge	7.1	0.12	18,319	0.05	45,798	0.02	91,596	0.003	667,424
	5	Murphys_Creek	7.1	0.05	45,798	0.02	114,495	0.01	228,990	0.001	1,668,559
	6	Dunback	7.1	0.07	34,472	0.03	86,179	0.01	172,358	0.002	1,255,905
	7	Flat_Stream-Glenpark	7.3	0.05	67,958	0.02	169,896	0.01	339,792	0.001	2,475,926
	8	Nichols_Rock	6.7	0.04	35,457	0.01	88,641	0.01	177,283	0.001	1,291,788
	9	Maungatua-North_Taieri	7.1	0.39	5,909	0.16	14,774	0.08	29,547	0.011	215,298
	10	Silver_Stream-Merton	7.0	0.16	12,694	0.06	31,736	0.03	63,472	0.004	462,492
	11	Waitahuna_Heights	6.9	0.14	11,326	0.06	28,316	0.03	56,632	0.004	412,654
	12	Waitahuna_Heights_2	6.7	0.04	33,487	0.01	83,717	0.01	167,434	0.001	1,220,022
	13	Kaikorai-Green_Island	6.9	0.05	31,517	0.02	78,792	0.01	157,585	0.001	1,148,256
	14	Akatore_North	7.1	0.14	17,236	0.06	43,090	0.03	86,179	0.395	6,171
	15	Akatore_South	6.9	0.07	21,668	0.03	54,170	0.01	108,339	0.002	789,426
	16	Titri_North	7.0	0.35	5,712	0.14	14,281	0.07	28,562	0.010	208,121
	17	Titri_Central	7.0	0.42	4,925	0.17	12,311	0.08	24,623	0.215	9,718
	18	Titri_South	7.0	0.21	9,521	0.08	23,802	0.04	47,604	0.006	346,869
	19	Takapu	7.4	0.04	110,309	0.01	275,773	0.01	551,546	0.001	4,018,895
	20	Tuapeka	7.3	0.01	251,150	0.01	627,876	0.00	1,255,752	0.000	9,150,162
	21	Waihemo	7.4	0.71	5,417	0.28	13,542	0.14	27,085	0.019	197,356
2.3	1+2	Hyde_Complete-The_Twins	7.6	0.51	10,533	0.20	26,332	0.10	52,665	0.07	76,378
	3	Horse_Flat	7.0	0.12	17,137	0.05	42,843	0.02	85,687	0.02	124,267
	4	Billys_Ridge	7.1	0.12	18,319	0.05	45,798	0.02	91,596	0.02	132,838
	5	Murphys_Creek	7.1	0.05	45,798	0.02	114,495	0.01	228,990	0.01	332,094
	6	Dunback	7.1	0.07	34,472	0.03	86,179	0.01	172,358	0.01	249,963
	7+8	Flat_Stream-Glenpark-Nichols_Rock	7.5	0.04	105,056	0.02	262,641	0.01	525,282	0.01	761,792
	9+10	Maungatua-North_Taieri-Silver_Stream-Merton	7.5	0.27	15,758	0.11	39,396	0.05	78,792	0.04	114,269
	11	Waitahuna_Heights	6.9	0.14	11,326	0.06	28,316	0.03	56,632	0.02	82,131
	12	Waitahuna_Heights_2	6.7	0.04	33,487	0.01	83,717	0.01	167,434	0.00	242,821
	13+14	Kaikorai-Green_Island-Akatore_North	7.4	0.08	50,652	0.03	126,630	0.02	253,261	0.29	14,185
	15	Akatore_South	6.9	0.07	21,668	0.03	54,170	0.01	108,339	0.01	157,120
	16	Titri_North	7.0	0.35	5,712	0.14	14,281	0.07	28,562	0.05	41,422
	17+18	Titri_Central-Titri_South	7.4	0.32	12,694	0.13	31,736	0.06	63,472	0.16	24,909
	19	Takapu	7.4	0.04	110,309	0.01	275,773	0.01	551,546	0.00	799,882
	20	Tuapeka	7.3	0.01	251,150	0.01	627,876	0.00	1,255,752	0.00	16,010,840
	21	Waihemo	7.4	0.71	5,417	0.28	13,542	0.14	27,085	0.55	6,907

MODEL	Fault-ID	FaultName	Mw	MODEL A		MODEL B		MODEL C		MODEL D	
				SR Ave	RI Ave	SR Ave	RI Ave	SR Ave	RI Ave	SR Ave	RI Ave
2.4	1+2	Hyde_Complete-The_Twins	7.6	0.51	10,533	0.20	26,332	0.10	52,665	0.06	91,370
	3	Horse_Flat	7.0	0.12	17,137	0.05	42,843	0.02	85,687	0.01	148,660
	4	Billys_Ridge	7.1	0.12	18,319	0.05	45,798	0.02	91,596	0.01	158,912
	5	Murphys_Creek	7.1	0.05	45,798	0.02	114,495	0.01	228,990	0.01	397,280
	6	Dunback	7.1	0.07	34,472	0.03	86,179	0.01	172,358	0.01	299,028
	7+8	Flat_Stream-Glenpark-Nichols_Rock	7.5	0.04	105,056	0.02	262,641	0.01	525,282	0.00	911,323
	9+10	Maungatua-North_Taieri-Silver_Stream-Merton	7.5	0.27	15,758	0.11	39,396	0.05	78,792	0.03	136,698
	11	Waitahuna_Heights	6.9	0.14	11,326	0.06	28,316	0.03	56,632	0.02	98,252
	12	Waitahuna_Heights_2	6.7	0.04	33,487	0.01	83,717	0.01	167,434	0.00	290,484
	13	Kaikorai-Green_Island	6.9	0.05	31,517	0.02	78,792	0.01	157,585	0.01	273,397
	14+15	Akatore_North-Akatore_South	7.4	0.11	38,083	0.04	95,207	0.02	190,415	0.32	12,671
	16+17	Titri-North_Titri-Central	7.4	0.39	10,386	0.16	25,966	0.08	51,931	0.20	20,464
	18	Titri_South	7.0	0.21	9,521	0.08	23,802	0.04	47,604	0.02	82,589
	19	Takapu	7.4	0.04	110,309	0.01	275,773	0.01	551,546	0.00	956,889
	20	Tuapeka	7.3	0.01	251,150	0.01	627,876	0.00	1,255,752	0.00	16,010,840
	21	Waihemo	7.4	0.71	5,417	0.28	13,542	0.14	27,085	0.55	6,907
3	1+2	Hyde_Complete-The_Twins	7.6	0.51	10,533	0.20	26,332	0.10	52,665	0.10	54,047
	3	Horse_Flat	7.0	0.12	17,137	0.05	42,843	0.02	85,687	0.02	87,935
	4	Billys_Ridge	7.1	0.12	18,319	0.05	45,798	0.02	91,596	0.02	94,000
	5	Murphys_Creek	7.1	0.05	45,798	0.02	114,495	0.01	228,990	0.01	234,999
	6	Dunback	7.1	0.07	34,472	0.03	86,179	0.01	172,358	0.01	176,881
	7+8	Flat_Stream-Glenpark-Nichols_Rock	7.5	0.04	105,056	0.02	262,641	0.01	525,282	0.01	539,066
	9+10	Maungatua-North_Taieri-Silver_Stream-Merton	7.5	0.27	15,758	0.11	39,396	0.05	78,792	0.05	80,860
	11	Waitahuna_Heights	6.9	0.14	11,326	0.06	28,316	0.03	56,632	0.03	58,118
	12	Waitahuna_Heights_2	6.7	0.04	33,487	0.01	83,717	0.01	167,434	0.01	171,827
	13+14+15	Kaikorai-Green_Island-Akatore_Complete	7.6	0.08	71,789	0.03	179,471	0.02	358,943	0.27	21,292
	16+17+18	Titri_Complete	7.7	0.33	18,361	0.13	45,904	0.07	91,807	0.17	36,116
	19	Takapu	7.4	0.04	110,309	0.01	275,773	0.01	551,546	0.01	566,019
	20	Tuapeka	7.3	0.01	251,150	0.01	627,876	0.00	1,255,752	0.00	16,010,840
	21	Waihemo	7.4	0.71	5,417	0.28	13,542	0.14	27,085	0.55	6,907

A3.0 ADDRESSING UNCERTAINTY IN FAULT SOURCE BEHAVIOUR THROUGH A LOGIC TREE APPROACH

We have developed three different models for fault rupture length (used to estimate Mw), models 1, 2 and 3 (Figure 1.9.1 in main text). In Model 1, fault sources are defined as individual fault segments) as represented in Figure 1.8.1 (e.g., the Titri Fault ruptures in three independent segments, namely north central and south). In Model 2, we allow for two contiguous segments of the longer fault sources to rupture together (i.e., we join two segments into one) (e.g., the Titri Fault ruptures in two independent segments, such as the north+central, leaving the south segment to rupture independently). In Model 3, we allow for three or more segments or faults to rupture at once (e.g., the Titri Fault ruptures in one segment, namely north+central+south; or a combined rupture of Kaikorai_GreenIsland+AkatoreN+AkatoreSouth). Longer rupture lengths result in larger Mw than shorter ruptures (see Appendix 3).

Recurrence intervals (RIs) for the various fault models are more challenging to assess than Mws. In intraplate areas and other areas of low seismicity worldwide, some studies have suggested that fault activity occurs episodically (e.g. Clark et al. 2012), i.e., time periods of clustered activity followed by longer time periods of quiescence. In the Dunedin area, the Akatore Fault shows evidence for this behaviour, with quiescence of 110,000 years or more, followed by three ground rupturing earthquakes in the last 10,000 years (Taylor-Silva 2017). This means that some faults that are currently in phases of quiescence will could become active again in the future. It is challenging to assess the likely future activity of such quiescent faults due to the absence of deformation evidence in the landscape and latest Quaternary (125,000 years) geologic record.

We derive the RI for faults from single event displacement (the amount the fault moves in ground-rupturing earthquake) and slip rate (time-averaged velocity at which faults move) values (method from Stirling et al., 2012). To account for uncertainty in fault activity rates, we consider four alternative slip rate models for the region (A to D Figure 1.9.1). Models A to C use the long-term fault behaviour to define fault activity. In Model A, we infer that the fault displacements of the schist basement erosion surface have been accumulating since the inception of the current tectonic regime, which we assign as 2 Ma in this model. Models B and C are similar to A but have inception ages of 5 and 10 Ma, respectively. Model D attempts to represent the current pattern of fault activity rate as defined from paleoseismic data for the Akatore and Titri faults, and geodetic models of crustal deformation across the region for the remaining faults. We thus assign the paleoseismic slip rates to the Akatore and Titri faults, and for the remainder of faults we assign a portion of the preliminary current deformation rate estimated with geodetic measurements (GNSS results from Research Aim 1.5). The slip rate assigned to the reminder faults is proportional to the amount of displacement of the WES along each fault.

In the logic tree (Figure 1.9.1) each segmentation model is combined with each slip rate model. Therefore, we obtain 12 (3 x 4) different final models for the calculations with a weight each that is carried from the combination of the models it is built from. Model 2 has additional options from different combinations of segments (e.g., the Titri Fault has two options: a) north+central and south; or b) north and central+south), of which we have selected two representative ones. Therefore, our final total number of models is 16 rather than 12. Calculated earthquake parameters for fault sources in the wider Dunedin area are listed in Appendix 3.

A4.0 SHAKEMAPNZ METHODS

ShakeMapNZ uses Intensity Prediction equations (IPE) with macroseismic data from around the globe and specifically from New Zealand (Dowrick and Rhoades, 2005). In addition, to correct for the bias of inter-event uncertainty in the IPE, instrumental ground motions are converted to macroseismic intensity using the Ground Motion Conversion equation (GMICE) from Worden et al. (2012). This GMICE is based on data from California, and thus it’s not New Zealand specific. The intensities in the ShakeMaps correspond to the current version of the New Zealand Modified Mercalli (MM) intensity scale (Dowrick et al., 2008).

A5.0 MODIFIED MERCALLI INTENSITY SCALE (DOWRICK ET AL., 2008) FOR MMI VALUES MENTIONED IN THIS STUDY

MM 6

People

Felt by all. People and animals alarmed. Many run outside.* Difficulty experienced in walking steadily.

Fittings

Objects fall from shelves. Pictures fall from walls (H*). Some furniture moved on smooth floors, some unsecured free-standing fireplaces moved. Glassware and crockery broken. Very unstable furniture overturned. Small church and school bells ring (H*). Appliances move on bench or table tops. Filing cabinets or "easy glide" drawers may open (or shut).

Structures

Slight damage to Buildings Type I*. Some stucco or cement plaster falls. Windows Type I* broken. Damage to a few weak domestic chimneys, some may fall.

Environment

Trees and bushes shake, or are heard to rustle. Loose material may be dislodged from sloping ground, e.g. existing slides, talus and scree slopes. A few very small (≤103 m3) soil and regolith slides and rock falls from steep banks and cuts. A few minor cases of liquefaction (sand boil) in highly susceptible alluvial and estuarine deposits.

MM 7

People

General alarm. Difficulty experienced in standing. Noticed by motorcar drivers who may stop.

Fittings

Large bells ring. Furniture moves on smooth floors, may move on carpeted floors. Substantial damage to fragile* contents of buildings.

Structures

Unreinforced stone and brick walls cracked. Buildings Type I cracked with some minor masonry falls. A few instances of damage to Buildings Type II. Unbraced parapets, unbraced brick gables, and architectural ornaments fall. Roofing tiles, especially ridge tiles may be dislodged. Many unreinforced domestic chimneys damaged, often falling from roof-line. Water tanks Type I* burst. A few instances of damage to brick veneers and plaster or cement-based linings. Unrestrained water cylinders (Water Tanks Type II*) may move and leak. Some windows Type II* cracked. Suspended ceilings damaged.

Environment

Water made turbid by stirred up mud. Small slides such as falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings common. Instances of settlement of unconsolidated, or wet, or weak soils. A few instances of liquefaction (ie. small water and sand ejections). Very small (≤103 m3) disrupted soil slides and falls of sand and gravel banks, and small rock falls from steep slopes and cuttings are common. Fine cracking on some slopes and ridge crests. A few small to moderate landslides (103 –105 m3), mainly rock falls on steeper slopes (>30º) such as gorges, coastal cliffs, road cuts and excavations. Small

discontinuous areas of minor shallow sliding and mobilisation of scree slopes in places. Minor to widespread small failures in road cuts in more susceptible materials. A few instances of non-damaging liquefaction (small water and sand ejections) in alluvium.

MM 8

People

Alarm may approach panic. Steering of motorcars greatly affected.

Structures

Buildings Type I heavily damaged, some collapse*. Buildings Type II damaged, some with partial collapse*. Buildings Type III damaged in some cases. A few instances of damage to Structures Type IV. Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down. Some pre-1965 infill masonry panels damaged. A few post-1980 brick veneers damaged. Decayed timber piles of houses damaged. Houses not secured to foundations may move, and damage to earthenware sanitary fittings may occur. Most unreinforced domestic chimneys damaged, some below roof-line, many brought down.

Environment

Cracks appear on steep slopes and in wet ground. Significant landsliding likely in susceptible areas. Small to moderate (103 –105 m3) slides widespread; many rock and disrupted soil falls on steeper slopes (steep banks, terrace edges, gorges, cliffs, cuts etc.). Significant areas of shallow regolith landsliding, and some reactivation of scree slopes. A few large (105 –106 m3) landslides from coastal cliffs, and possibly large to very large (≥106 m3) rock slides and avalanches from steep mountain slopes. Larger landslides in narrow valleys may form small temporary landslide-dammed lakes. Roads damaged and blocked by small to moderate failures of cuts and slumping of road-edge fills. Evidence of soil liquefaction common, with small sand boils and water ejections in alluvium, and localised lateral spreading (fissuring, sand and water ejections) and settlements along banks of rivers, lakes, and canals etc. Increased instances of settlement of unconsolidated, or wet, or weak soils.

MM 9

Structures

Many Buildings Type I destroyed*. Buildings Type II heavily damaged, some collapse*. Buildings Type III damaged, some with partial collapse*. Structures Type IV damaged in some cases, some with flexible frames seriously damaged. Damage or permanent distortion to some Structures Type V. Houses not secured to foundations shifted off. Brick veneers fall and expose frames.

Environment

Cracking of ground conspicuous. Landsliding widespread and damaging in susceptible terrain, particularly on slopes steeper than 20º. Extensive areas of shallow regolith failures and many rock falls and disrupted rock and soil slides on moderate and steep slopes (20º -35º or greater), cliffs, escarpments, gorges, and man-made cuts. Many small to large (10^3 –10^6 m^3) failures of regolith and bedrock, and some very large landslides (10^6 m^3 or greater) on steep susceptible slopes. Very large failures on coastal cliffs and low-angle bedding planes in Tertiary rocks. Large rock/debris avalanches on steep mountain slopes in well-jointed greywacke and granitic rocks. Landslide-dammed lakes formed by large landslides in narrow valleys. Damage to road and rail infrastructure widespread with moderate to large failures of road cuts and slumping of road-edge fills. Small to large cut slope failures and rock falls in open mines and quarries. Liquefaction effects widespread with numerous sand boils and water ejections on alluvial plains, and extensive, potentially damaging lateral spreading (fissuring and sand ejections) along banks of rivers, lakes, canals etc). Spreading and settlements of river stop-banks likely.

Construction Types

Buildings Type I

Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick or rammed earth. Soft storey structures (e.g. shops) made of masonry, weak reinforced concrete or composite materials (e.g. some walls timber, some brick) not well tied together. Masonry buildings otherwise conforming to buildings Types I to III, but also having heavy unreinforced masonry towers. (Buildings constructed entirely of timber must be of extremely low quality to be Type I.)

Buildings Type II

Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces. Such buildings not having heavy unreinforced masonry towers.

Buildings Type III

Reinforced masonry or concrete buildings of good workmanship and with sound mortar, but not formally designed to resist earthquake forces.

Structures Type IV

Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special collapse or damage limiting measures taken (mid-1930s to c. 1970 for concrete and to c. 1980 for other materials).

Structures Type V

Buildings and bridges, designed and built to normal use standards, i.e. no special damage limiting measures taken, other than code requirements, dating from since c. 1970 for concrete and c. 1980 for other materials.

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