# Seismic interpretation of the Canterbury Plains, New Zealand

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## INTRODUCTION

New Zealand is a seismically active region, located within a complex tectonic environment. The 2010-2011 Canterbury earthquake sequence in the Canterbury Plains on the South Island of New Zealand ruptured previously unknown fault systems, and resulted in severe damage to infrastructure and loss of life. The region continues to experience aftershock activity in the present day. Identifying faults in seismically active populated areas is essential in geotechnical engineering applications and seismic hazard risk assessment in earthquake studies. Seismic reflection and imaging techniques provide a means to identify and characterize fault zones, and an understanding of the regional tectonics and geology is essential for interpreting the seismic data.

### Geographic setting of the study area

The Canterbury Region on the South Island of New Zealand (Figure 1a) is the largest government administrated region in all of New Zealand. The region includes the Canterbury Plains, the city of Christchurch, the Clarence River catchment to the north, the Waitaki River catchment to the south, and the mountains to the west (Environment Canterbury, 2013a). The Canterbury Plains are constrained within the Canterbury Region, and are bound by the foothills of the Southern Alps to the west, and Banks Peninsula and the Pacific Ocean to the east (Figure 1b). The Northern Canterbury Plains border basin and range topography, whereas flat alluvial outwash plains are represented by the central area (Forsyth et al., 2008).

Two areas are of interest for this research. The first location is on the east coast of the Canterbury Region in the city of Christchurch, and the second area of interest is located in the central Canterbury Plains; these areas are shown in the red highlighted rectangles in Figure 1.

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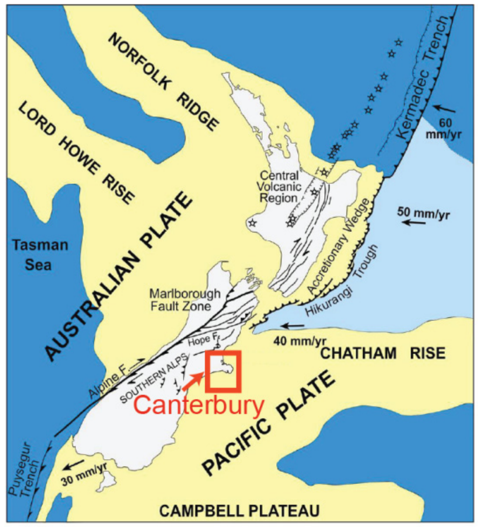


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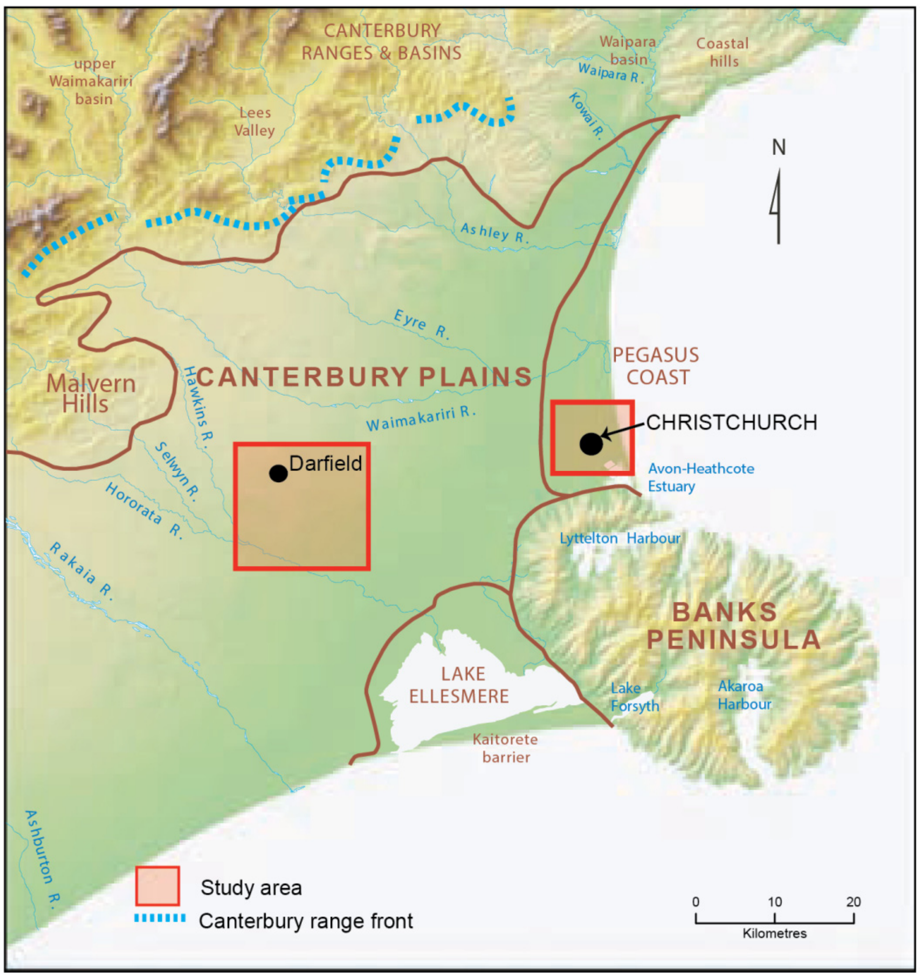



Figure 1. (a) New Zealand plate tectonics, with the Canterbury Region indicated. (b) Map of the Canterbury Plains and surrounding area, overlaying a shaded topographic relief model. Figure adapted from Forsyth et al. (2008).

## The 2010-2011 Canterbury Earthquake sequence

The Canterbury earthquake sequence includes the 4 September 2010 Darfield earthquake with an epicenter approximately 40 km west of Christchurch, the 22 February 2011 Christchurch earthquake, the 6 June 2011 aftershock, and the 23 December 2011 New Brighton aftershock sequence. The focus of this research is on the Darfield and Christchurch events. The fault ruptures are described by Beaven et al. (2012) as a rupturing of intact rock rather than a smoother rupture along a well developed plate boundary, since the fault surfaces have been immobile for a long period of time, which is characteristic of an intraplate setting. The earthquake sequence is related to coexisting strike-slip and thrust activity on an evolving thrust system (Campbell et al., 2012) in the upper crust. The earthquakes occurred along previously unknown faults. The first two larger earthquakes of the sequence involved rupturing of the Greendale Fault and Port Hills Fault (Figure 2).

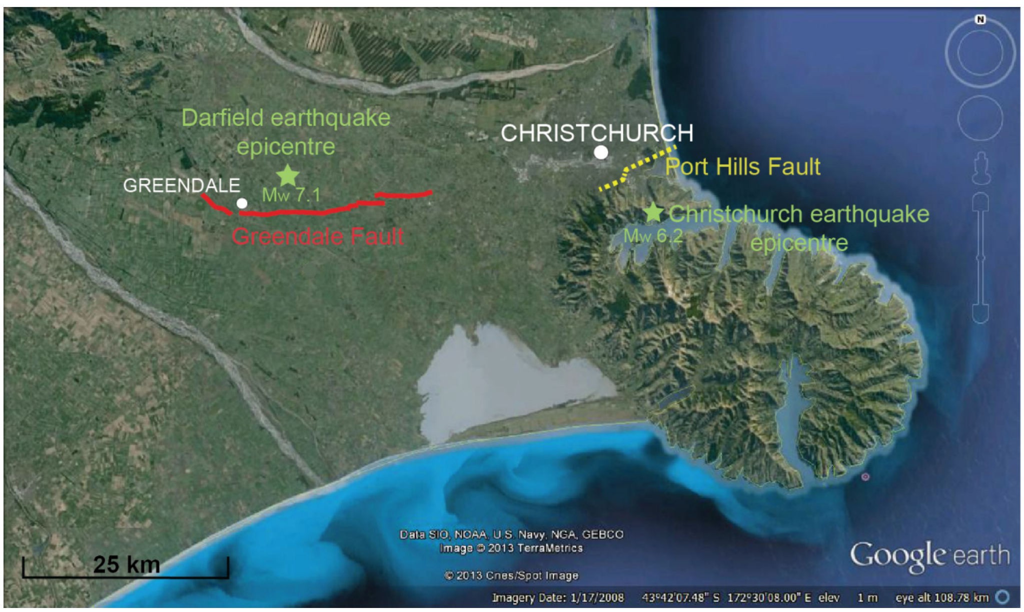



Figure 2. Map showing fault trace of the Greendale Fault (in red) which ruptured the surface on 4 September 2011 during the Darfield earthquake. The Port Hills Fault (in dashed yellow) is the surface projected fault location based on GPS and DInSAR data from Beaven et al. (2012). Event epicentres are green stars. Google earth V 7.0.3.8542. (17 Jan 2013) New Zealand. 43°42'07.48"S, 172°30'08.00"E, Eye alt 108.78 km. SIO, NOAA, U.S. Navy, NGA, GEBCO. Cnes/Spot Image 2013. http://www.earth.google.com [May 30, 2013].

### *The 4 September 2010 Darfield Earthquake*

The 7.1 moment magnitude (Mw) Darfield earthquake initiated 11 km below the Canterbury Plains in a low relief rural farming area, with an epicenter approximately 6 km southeast from the town of Darfield on a previously unknown fault system (Sibson et al., 2012). Multiple fault planes ruptured, with the Greendale Fault undergoing most of the earthquake's moment release and caused rupturing of the ground surface (Beaven et al., 2010; Beaven et al., 2012). The Greendale Fault rupture was triggered a few kilometers to the north of the main rupture by the NE trending blind Charing Cross Fault, an Mw 6.3 event on a steeply dipping reverse fault segment (Beaven et al., 2010; Gledhill et al., 2011). The Greendale Fault ruptured in both the east and west directions and the rupturing occurred over approximately 10 seconds, followed 17 seconds later by a third fault rupture at the western end of the Greendale Fault near Horotata, a Mw 5.7 event with a reverse right lateral component mechanism (Holden et al., 2011). An image of part of the Greendale Fault is shown in Figure 3.

The complex Greendale Fault rupture is the main source of the rupture sequence (Holden et al., 2011), and is generally described by three fault segments: the main E-W trending dextral strike-slip fault rupture, a fault segment to the west of the main rupture trending NW, and an offset right-lateral fault segment trending NE to the east of the main rupture (Beaven et al., 2010). Deformation features including left step-overs are observed with associated push up structures (Villamore et al., 2012) with an average strike of 085° for the left-stepping fault traces (Sibson et al., 2012).

Figure 3. Aerial photograph of the E-W trending Greendale Fault. A drainage canal is displaced by shear fractures along the fault surface. Image taken by Richard Jongens of GNS science.

The mainly dextral strike-slip surface rupture extends east-west for approximately 30 km (Quigley et al., 2010). Measured displacement and deformation includes approximately up to 5 m of predominantly dextral displacement (2.5 m average displacement), vertical displacement at fault bends was measured at 1 – 1.5 m, and a 30 – 300 m wide deformation zone exists perpendicular to the strike of the fault (Holden et al., 2011; Van Dissen et al., 2011). Ground displacement to the north of the Greendale Fault is generally eastward, with uplift to the south of the fault (Beaven et al., 2010). More ground deformation is present on the western end of the fault (Campbell et al., 2012). The surface deformation from the Darfield earthquake is complex. Van Dissen et al. (2011) describe the fault structures in areas of maximum deformation as "E-SE striking Riedel fractures with right-lateral displacements, SE striking extensional fractures, S-SE to S striking Riedel fractures with left-lateral displacements, NE striking thrusts, horizontal dextral flexture, and decimenter-amplitude vertical flexture and bulging." An image of fault step-overs and bulging is shown in Figure 4.

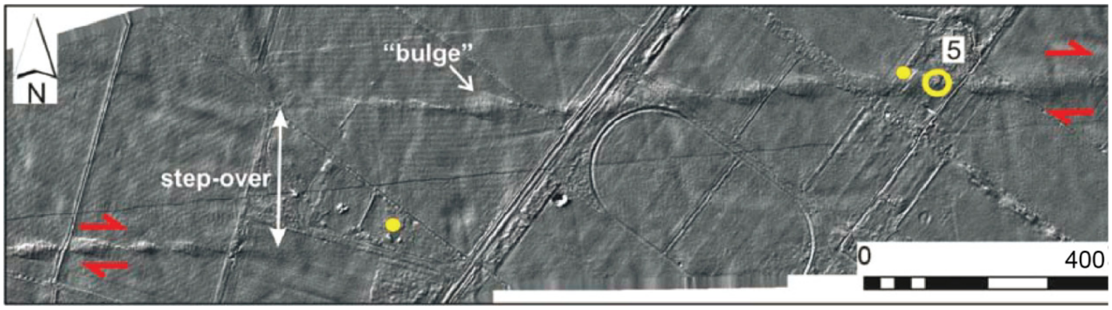



Figure 4. LiDAR hillshade DEM along the Greendale Fault demonstrating a left stepping en echelon rupture. Fault step-over and bulges are indicated. Red arrows indicate lateral displacement. Yellow circles denote damaged buildings. Image adapted from Van Dissen et al. (2011).

The Darfield earthquake caused significant damage to buildings near the fault rupture, and also to many older buildings in Christchurch, mostly as a result of differential settlement of foundations due to liquefaction and lateral spreading (Gledhill et al., 2011). Over 5000 aftershocks were measured seven months following the Darfield earthquake, most with focal depths less than 15 km (Sibson et al., 2012).

*The 22 February 2011 Christchurch Earthquake*

Following the Darfield earthquake, right lateral deformation occurred to the east of the Greendale Fault (Beaven et al., 2012) causing a change in the crustal stress regime near Christchurch. On 22 February 2011, a 6.2 Mw earthquake occurred with an epicenter approximately 6 km SE of Christchurch city center on a previously unknown fault with multiple fault plane ruptures (Bannister and Gledhill, 2012). A surface rupture did not occur, but uplift occurred to the south of the surface projection of a fault, now known as the Port Hills Fault, resulting in extensive damage and loss of life. The earthquake focus was at a depth of approximately 4 km, and was initially modelled on a planar fault striking NE-SW at approximately 59° and dipping 69° SE with a mixture of right-lateral and reverse slip (Beaven et al. 2011). Beaven et al. (2011) later provided a two-fault model with slip on two sub-parallel fault planes to provide a better fit to the geodetic source data. Beaven et al. (2012) again further updated the model to three fault segments with oblique-reverse/right-lateral slip on the eastern fault section, right-lateral slip on the western fault section, and pure reverse faulting on the NNE-trending cross fault. Maximum slip is determined to be 2.5-3 m for the geodetic model.

*Aftershocks*

After the Darfield and Christchurch earthquakes, there still remained a continuation of complex aftershocks. As of May 2013, over 11850 earthquakes have been recorded in the last year in the Canterbury region, with 13 events having Mw 4 to 5 (GeoNet, 2013). A region identified between the Darfield and Christchurch epicentres is identified where significant moment release has not occurred, and may possibly fail in the near future (Beaven et al., 2012).

### Objectives

Hidden fault structures have been suspected in the Canterbury Plains (Pettinga et al., 2001); however the region has been largely unstudied with very little well control and a lack of seismic data. This research contributes to constraining seismic hazard and risk assessment by identifying the presence of faults beneath the central Canterbury plains and within the city of Christchurch in newly acquired 2D seismic profiles. The main goals of this research were a seismic study of active faults using newly acquired 2D seismic reflection data from the Canterbury Plains and within the city of Christchurch, following the 2011 Christchurch earthquake. The approach was seismic interpretation of the newly acquired data with the following objectives:

- Provide a review of the tectonic and geologic background of New Zealand with a focus on the Canterbury Plains, in order to complement seismic interpretation of the region.

- Interpretation of the 2D seismic reflection data in the city of Christchurch and the Canterbury Plains by delineating local stratigraphy and mapping fault systems for seismic risk hazard assessment.

### Datasets and software used

The 2D seismic reflection data used for interpretation was processed by Sensor Geophysical Ltd. in Calgary, Alberta. Final processed 2D post-stack migrated seismic sections were used for interpretation using the IHS Kingdom® Suite Interpretation Package. Google Earth™ 7.0.3.8542 was used to generate maps. Adobe® Illustrator® CS6 and Microsoft® PowerPoint® were used to construct and edit figures.

## TECTONIC AND GEOLOGIC OVERVIEW

New Zealand is a region of active earthquake activity and is structurally complex. The active oblique convergent Australian-Pacific plate boundary zone underlies New Zealand from the northeast to the southwest. The Pacific plate subducts beneath the Australian plate along the east coast of the North Island, the Australian plate subducts under the Pacific plate south of the South Island, and an oblique transform fault system occurs in between. The converging plate boundary on the South Island of New Zealand has resulted in compressional deformation and rapid uplift of the Southern Alps. Since the last glacial period during the Late Quaternary, the Canterbury Plains have been buried by eroded greywacke sediments transported in eastbound rivers from the Southern Alps by glaciations and fluvial outwash (Wilson, 1985). This thick layer of quaternary unconsolidated sediment blankets geologic structure, including hidden faults which were activated during the 2010-2011 Canterbury earthquake sequence. A review of the tectonic history of New Zealand with a focus of the South Island and Canterbury Region is given to provide a general understanding of the current plate boundaries. An overview of the geologic stratigraphy of the Canterbury Plains is presented to support interpretation of seismic data analysis and observed geophysical trends

## The tectonic history of New Zealand

New Zealand was once part of the eastern Pacific margin of Gondwana and formed part of the Australia and Antarctic sectors of the Pacific-facing margin up until the Cretaceous period (Laird and Bradshaw, 2004). The history of Gondwana is summarized by Teichert (1959) as an idea originating and developing in the late nineteenth century. It was proposed that a large Indo-Oceanic super continent existed from early Permian time to the end of the Miocene. Gondwana is believed to have included the area of eastern South America, the southern Atlantic Ocean, central and southern Africa, the Indian Ocean, Peninsular India, Australia, and Antarctica (Molnar et al., 1975). The foundations of New Zealand were built during Paleozoic and Mesozoic sediment accretion processes, as a result of the Permian oceanic crust subducting beneath the eastern Gondwana margin (Cox and Sutherland, 2007).

Approximately 81 million years ago during the Late Cretaceous, the continent of Zealandia which includes New Zealand, the Campbell Plateau, and the Chatham rise, began to separate from Gondwana by rifting and sea floor spreading, and drifted to its current position by the opening of the Tasman Sea (Molnar et al., 1975). Cretaceous extension following rifting led to east and northeast trending normal faults at the Gondwana margin, and are mapped in the basement of the Chatham Rise and to the west in Canterbury region (Field et al., 1989). Seafloor spreading ended during the early Eocene (Cox and Sutherland, 2007). Following separation from Gondwana, Zealandia is regarded as a mostly submerged micro-continent with only ten percent of the continental crust emerged above sea level (Mortimer, 2004), exposing the North and South Islands of New Zealand.

Submergence of Zealandia during the Late Cretaceous to the Oligocene is associated with marine transgression and coal and clastic dominated deposition. Carbonate-dominated deposition then occurred at maximum submergence during the Oligocene to early Miocene through most of New Zealand, however, this occurred earlier in eastern areas such as the Canterbury Basin (Jongens et al., 1999; King, 2000;).

Tectonic plate motion reconstructions of the Late Eocene - early Oligocene (about 38 Ma) correspond with development of the Australian-Pacific plate boundary similar to present day (Molnar, 1975; King, 2000). The initiation of the Alpine fault on the South Island is debated (Cooper et al., 1987); however there is general agreement that the fault was first established during the Late Oligocene or Early Miocene (Cox and Sutherland, 2007; King, 2000) and became an active transform around 25 Ma (Norris et al., 1990, and references therein). Correspondingly, during the early Miocene in the last 24-30 Ma, the Pacific Plate began to subduct beneath the Australian plate along the Hikurangi Margin (Nichol et al., 2007). Intraplate volcanism followed in the mid to Late Miocene with three main active volcanoes on the South Island between 11 and 5.8 Ma: Lyttelton, Akaroa, and the Mt. Hebert Volcanic Groups (Hampton and Cole, 2009).

Marine regression, as well as uplift and erosion at convergent margins during the Pliocene-Pleistocene contributed to significant volume of coarse clastic sediment deposited throughout New Zealand basins (King, 2000). Glacial deposits and alluvial gravels dominated sedimentary deposition during the Quaternary period. Up until the present, continuing compression, uplift, and erosion of the Southern Alps contribute to sedimentation around the South Island, and plate boundary deformation zone continues to increase (Forsyth et al., 2008).

**The current tectonic setting of New Zealand**

The active oblique convergent Australian-Pacific plate boundary crosses New Zealand from the northeast to the southwest, with the North Island of New Zealand on the continental Australian Plate, and most of the South Island on the continental Pacific plate. A simplified image of the tectonic setting and plate boundaries is shown in Figure 5. The Hikurangi subduction system off the East Coast of the North Island dips westward subducting the Pacific plate under the Australian Plate, while the Puysegur subduction system southwest of the South Island dips eastward subducting the Australian plate under the Pacific plate (Davey et al., 1998). The oblique plate motion can be viewed as the vector sum of parallel and perpendicular movement along the plate boundary. The southwest motion of the Pacific plate relative to the Australian plate decreases from > 40 mm/yr northeast of the north island to approximately 30 mm/yr in the south (Townend et al., 2012).

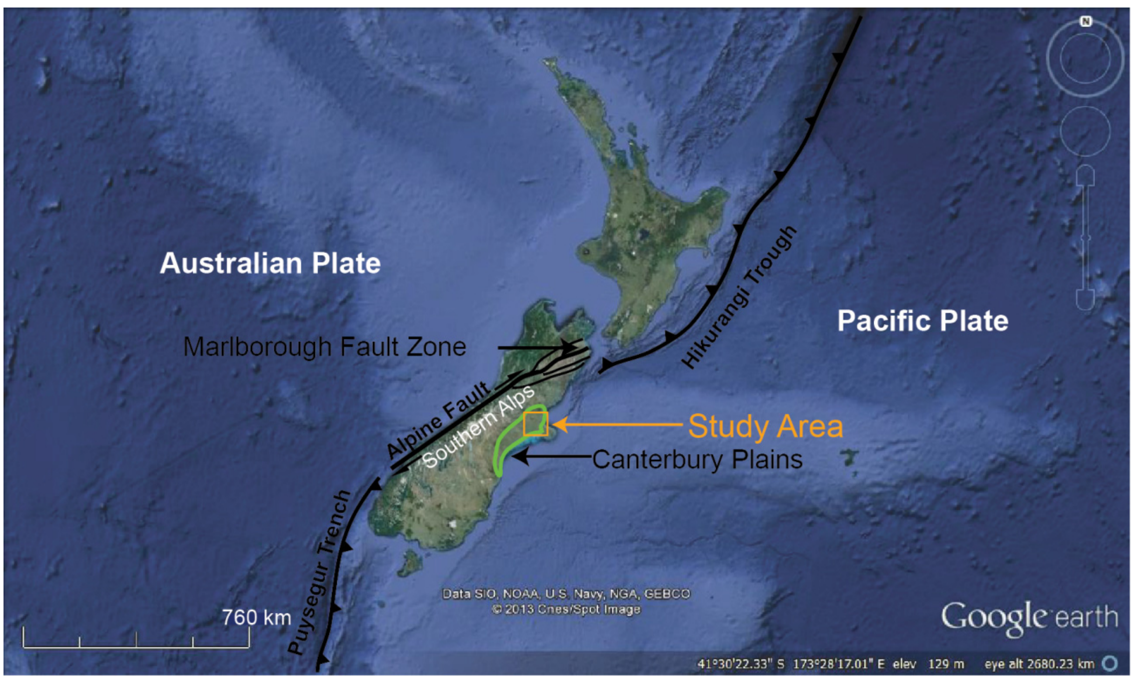



Figure 5. The tectonic setting of New Zealand, simplified. Google earth V 7.0.3.8542. (2013) New Zealand. 41°30'22.33"S, 173°28'17.01"E, Eye alt 2680.23 km. SIO, NOAA, U.S. Navy, NGA, GEBCO. Cnes/Spot Image 2013. http://www.earth.google.com [May 30, 2013].

At the Hikurangi subduction zone, the overriding Australian plate is deformed by a 480 km wide zone and is accompanied by strike-slip faulting throughout the central North Island (Nichol and Beaven, 2003). However, most of the convergent component of relative plate motion occurs on the Hikurangi subduction thrust, where there exists major thrust faults in the upper plate (Wallace et al., 2009). The Pacific Plate subducts beneath the Hikurangi trough at a rate of 5-6 cm/year (Campbell et al., 2012a). A shift in the plate motion mechanics then occurs in the northern South Island from oblique subduction to oblique transpression (Townend et al., 2012) with upper plate deformation and tectonics dominated by the strike-slip faults of the Marlborough Fault Zone at the northern end of the South Island (Eberhart-Phillips and Bannister, 2010). Large subduction thrusts are not expected beneath Marlborough and North Canterbury, as the subduction boundary is believed to be permanently locked (Reyners, 1998). Further southwest, oblique continental collision dominates most of the central South Island by means of the active Alpine Fault, where the Marlborough Fault Zone branches off. The Alpine Fault, with 480 km of right lateral slip since the Jurassic, delineates a transform boundary between the active Australian-Pacific plates (Norris et al., 1990). The compressional deformation through the central South Island has created rapid uplift of the Southern Alps mountain range through the central South Island to the east of the Alpine Fault (Kleffmann et al., 1998, Smith et al., 1995). Southwest and offshore of the South Island, the Australian plate subducts eastward below the Pacific plate along the Puysegur subduction zone , where a thrust faulted regime dominates (LaMarche and Lebrun, 2010; Townend et al., 2012).

**The tectonic setting of the Canterbury Region, South Island**

The Canterbury Region resides in an area of active earth deformation, as a result of oblique continental collision of the Australian and Pacific plates along the Alpine Fault to the west of the region (Stirling et al., 2001). At approximately the same latitude as Christchurch, the Australia-Pacific plate boundary motion is predicted to be 39 mm/yr at 43.5 °S at a bearing of N71 °E, along the N55 °E trending Alpine Fault (DeMets et al., 1990, p. 446). The oblique convergence slip estimates are approximately 35.5 mm/year parallel to the fault and 10 mm/year perpendicular to it, resulting in a transpressional zone boundary with strike-slip and dip-slip components (Norris and Cooper, 2001). The regional maximum compressive stress field ($\sigma 1$) is horizontal and is estimated to trend approximately 115° in the Canterbury Plains (Sibson et al., 2012).

For the most part, the Alpine Fault is an east-dipping oblique shear, projecting and flattening beneath west Canterbury where the crustal interface thins (Pettinga et al., 2001, Kleffman et al., 1998). The majority of plate boundary deformation is accommodated by the Alpine Fault; however 25% of the plate motion (±15% uncertainty) is divided among other structures across the 150-200 km wide Southern Alps into the Canterbury Region (Norris and Cooper, 2001; Jongens et al., 1999). The active tectonics of the continent-to-continent collision have the potential to activate existing buried faults in the Canterbury Plains (Campbell et al., 2012a). The rate of deformation of the Pacific Plate begins to subside from the Southern Alps towards the southeast in central and south Canterbury (Pettinga et al., 2001).

The upper crustal structure of the northern Canterbury Region is dominated by north and northeast trending faults and folds formed to accommodate plate motion between the Hikurangi Trench and the Alpine Fault, whereas the central and south Canterbury region is dominated by north trending active structures as a response to deformation from continent collision of the Southern Alps (Pettinga et al., 2001). The structures of the Canterbury Region are grouped by Pettinga et al. (2001) into structural domains (Figure 6). The focus area of this research is within Domain 7 in the Canterbury Plains Zone, which is generally described as a hidden and unstudied fault zone. Thrust and strike-slip faults are thought to have initiated in the foothills of western Canterbury, and spread with time into the plains as deformation expanded to the south and east (Campbell et al., 2012b).

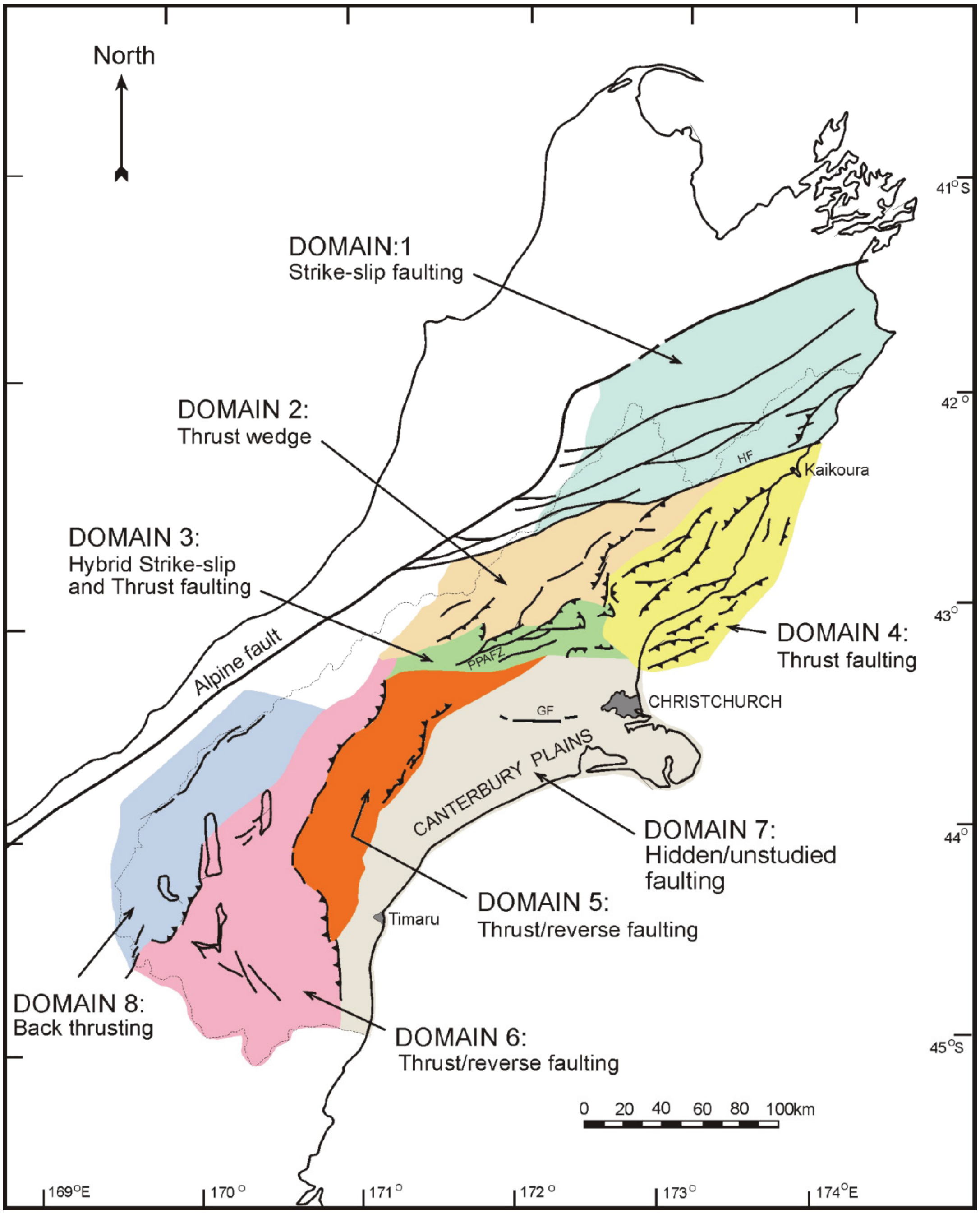



Figure 6. Structural domain map of New Zealand's South Island and the Canterbury Region from Pettinga et al. (2001). The focus of this research is located in Domain 7, where hidden faults are present. The Greendale Fault, which ruptured during the 4 September 2010 earthquake is marked as 'GF' within the boundary of the Canterbury Plains.

## Geologic setting and stratigraphy of the Canterbury Plains

*Permian to Early Cretaceous basement*

The basement rocks which form the foundation of the South Island in New Zealand are divided by the Median Tectonic Zone into a Western province, and an Eastern province which is also known as the New Zealand geosyncline (Landis and Coombs, 1967). Figure 7 shows a geologic map of the basement rocks on the South Island of New Zealand. The older Western province is composed of Paleozoic sedimentary rocks and various crystalline rocks of late Precambrian to Cretaceous age (MacKinnon, 1983). The younger Eastern province is composed of a collection of terranes which include a belt of clastic rock which belong to the Torlesse Composite Terrane (Mortimer, 2004) and underlie the Canterbury region. Terranes are defined as "fault-bounded slices of regional scale, each with their own distinctive geologic history" (Wandres and Bradshaw, 2005) and are divided by provenance, structural styles, lithologies, and low-grade metamorphic changes (Beetham and Waters, 1985). In many cases, the faults separating terrane boundaries in a suture zone are obscure (Howell et al., 1985).

The Torlesse rocks are fragments shed from continental margin basins, and are primarily quartzofeldspathic greywacke and gray-to-black mudstone (MacKinnon, 1983; Howell et al., 1985). The Torlesse is divided by the Esk-Head Melange into two sub-terranes which become younger eastward; The Permian-Triassic older Torlesse (Rakaia) which underlies most of the Southern Alps and eastern foothills of the Canterbury Plains, and the Late Jurassic-Early Cretaceous younger Torlesse (Pahau) in northeast Canterbury (Bishop et al., 1985, Wandres et al., 2004). The regional trend of the Mesozoic Torlesse terrane elongated boundaries reflect the northwest orientation of the Mesozoic Gondwana margin (Bradshaw et al., 1996; Cox and Sutherland, 2007). A structural basement high extends northwest from Banks Peninsula into the Canterbury Plains (Hicks, 1989).

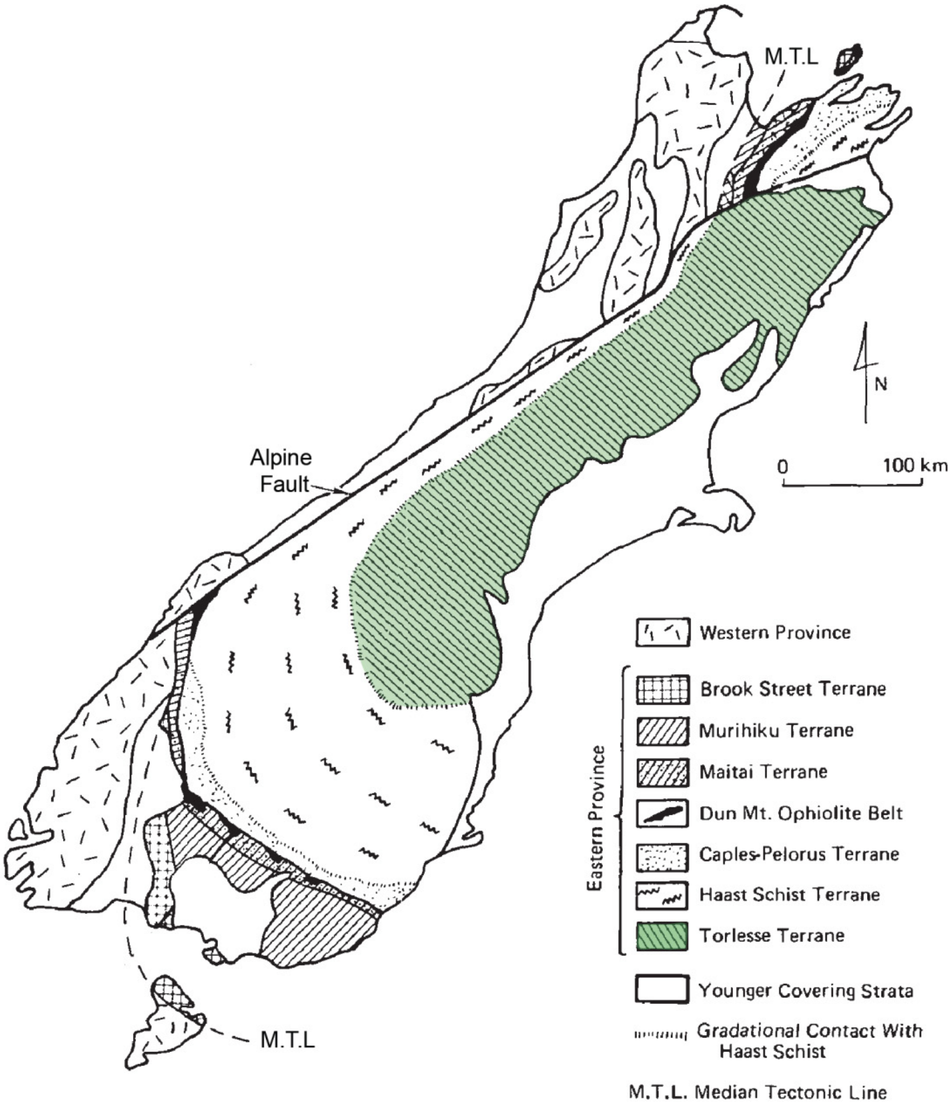
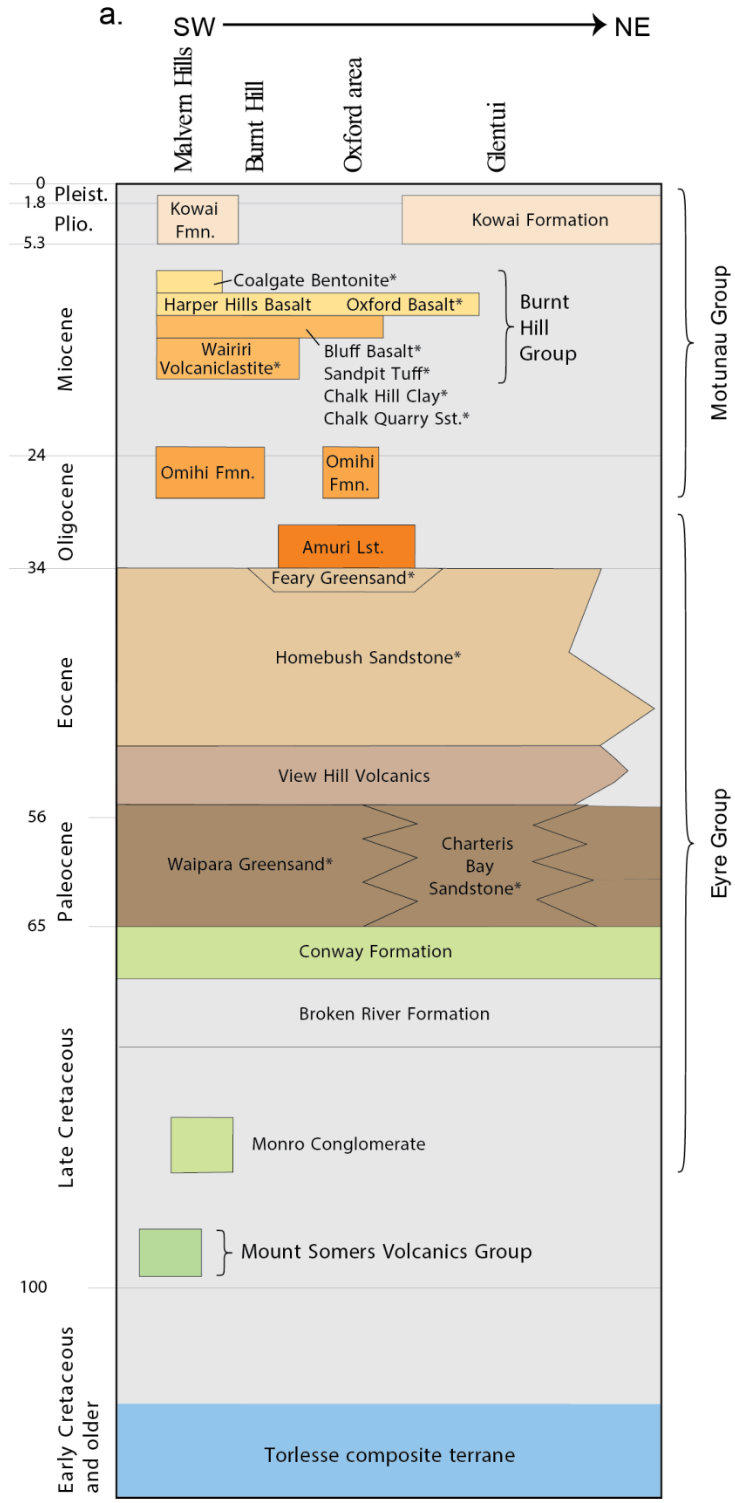



Figure 7. Geologic map of basement rocks on the South Island of New Zealand. Adapted from MacKinnon (1983). The Torlesse terrane, part of the Eastern province is highlighted in green.

### *Late Cretaceous to Pleistocene volcanic and sedimentary rocks*

This section provides a stratigraphic summary of southwest Canterbury in the Malvern Hills, Burnt Hill, and Oxford areas, and is based on Forsyth et al. (2008) and references therein. A stratigraphic chart listing geologic successions since the Early Cretaceous is shown in Figure 8. The central Canterbury region is characterized by a 1 - 2 km thick blanket of sedimentary and minor volcanic rocks of late Cretaceous to Cenozoic age overlying the greywacke basement (Browne et al., 2012). The sediment thickness is relatively constant between Banks Peninsula and the foothills of the Southern Alps.



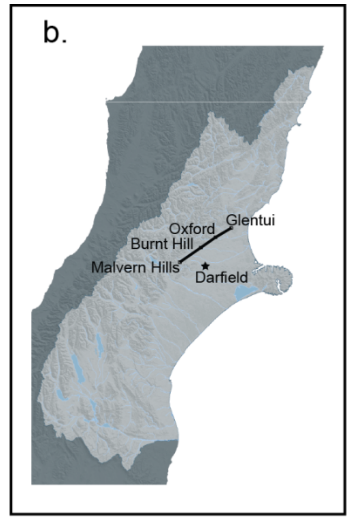




Figure 8. (a) Stratigraphic chart of the western Canterbury Plains. Adapted from Forsyth et al. (2008). (b) Map area showing location of (a). Adapted base map provided by Environment Canterbury.

The Mt. Somers Volcanic group erupted during late Cretaceous (89 ± 2 Ma) rifting and extension, and contains sequences of lavas, ignimbrites, and tuffs up to 1 km thick which unconformably overlay the eroded Torlesse rocks (Barley, 1987). West of Darfield in the Malvern Hills area (Figure 1), the middle late Cretaceous Monro conglomerate overlies the Mt. Somers volcanic group and older Torlesse rocks and is interpreted as a localised fault-angle depression filled with braided-river deposits.

During the latest Cretaceous to early Oligocene, a sedimentary succession of interbedded non-marine and marine sandstone and mudstone in the Eyre group is a result of subsidence in a passive margin setting throughout southwest Canterbury. The Eyre group also consists of the early Eocene intraplate View Hill Volcanics, and the Amuri Limestone found outcropping north of Darfield. Unconformities representing 3 to 10 million year time gaps separate the Eyre Group from the overlying limestone Omihi Formation of the Motunau Group.

The Motunau Group is composed of late Oligocene through early Pleistocene strata and is widespread, yet laterally intermittent sedimentary rock sequence beneath the Canterbury Plains. The Motunau Group also includes the middle to late Miocene Burnt Hill Group, an assembly of volcaniclastic rocks, basaltic flows, and sedimentary rocks. During the late Miocene, intraplate volcanisism resulted in the formation of large overlapping stratovolcanoes on Banks Peninsula: Lyttelton to the northwest, and Akaroa in the southeast of the peninsula.

The late Pliocene to early Pleistocene alluvial Kowai Formation caps Motunau Group rocks, and is up to several hundred meters thick in central and northern Canterbury. The weathered greywacke gravel resulted from rapid uplift and erosion of the Southern Alps.

*Quaternary Sedimentary deposits*

Sedimentary deposition during the Quaternary Period in the Canterbury region is dominated by glacial events and thick accumulations of alluvial gravel in structural depressions, including the late Pliocene to early Pleistocene Kowai gravels (Pillans, 1991). A considerable amount of glacial melt water and unconsolidated debris flooded many South Island rivers. The large area of river deposits in the Canterbury Plains consist mostly of unweathered alluvium with well-preserved channel patterns (Forsyth et al., 2008). During the Holocene, windblown fine grained silt (loess) was deposited with thickness of 2 to 4 meters, covering the widespread unconsolidated sediments (Pillans, 1991; Forsyth et al., 2008). Quaternary volcanism does not exist in the Canterbury region.

## ADDITIONAL INFORMATION FOR SEISMIC INTERPRETATION

This section provides a record of data available that will support the seismic interpretation. This included petroleum and water wells, previous geophysical work in the area, and also an overview of the earthquake history in the region.

### Wells

Exploration wells in the Canterbury Plains are sparse. The Leeston-1 and Arcadia-1 wells are closest to Darfield and the Greendale Fault zone, however they are not near

(Figure 9). Petroleum development and exploration activity increased during the 1960's in New Zealand when a major gas field was discovered off the North Island Taranaki coast (Katz and Kliewer, 1970). The Leeston-1 test well was drilled in 1969 and reached the Mesozoic greywacke basement at just over 1000 m depth. The Leeston-1 well is located approximately 20 km south from the Greendale Fault. The Arcadia-1 well was drilled in 2000 and is located approximately 20 km north from the Greendale Fault.

A 433 m deep Environment Canterbury water well named the Bexley testbore (well no. M35/6038), is used for reference in the seismic interpretation of the Christchurch seismic data, and is located within the city of Christchurch.


Figure 9. Map showing petroleum wells Arcadia-1 (drilled in 2000) and Leeston-1 (drilled in 1969). Google earth V 7.0.3.8542. (4 September 2013) New Zealand. 43°35'13.73"S, 172°22'30.02"E, Eye alt 148.29 km. SIO, NOAA, U.S. Navy, NGA, GEBCO. TerraMetics 2013. http://www.earth.google.com [June 29, 2013].

## Previous geophysical work

Geophysical investigations in the Canterbury Plains are limited, especially prior to the 2010-2011 Canterbury earthquake sequence. Most previous research is focused in the northwest Canterbury Plains near the Malvern Hills. This section summarizes key geophysical investigations during the past fifty years which were considered in this research.

In 1963, a seismic reflection survey consisting of 9 seismic lines totalling 280 km was acquired throughout the Canterbury Plains and is documented in Kirkaldy et al. (1963). Interestingly, Line 8 intersects the present day Greendale Fault surface rupture, however the data is too poor of quality to identify geologic structures. Horizons identified include Quaternary gravels and the geologic basement.

More recently, seismic data has been used to better characterize the Canterbury Plains in terms of potential seismic hazard. Jongens et al. (1999) reported on the structure and stratigraphy of the onshore Canterbury Plains using processed seismic data acquired by Indo-Pacific Energy (NZ) Ltd. The report summarized that basement faults contribute to active deformation in the overlaying strata, and major thrust faults were identified in the seismic lines to the northwest of the study area of this study. Finnemore (2004) used integrated geological and geophysical surveys to develop groundwater aquifer models, and characterize sedimentary units and a major fault zone in the northwest Canterbury Plains. The identified fault zone in the study is indicative of geologic structure from the western range front extending below the Canterbury Plains. Dorn et al. (2010) acquired and interpreted shallow seismic data with an aim to study seismogenic structures below the Canterbury Plains northwest of Darfield and the Malvern Hills, nestled against the Foothills of the Southern Alps. The seismic sections in the study provide evidence of intensely faulted and folded basement and Late Cretaceous-Tertiary layers. Gentle folding was shown to exist in the Quaternary layers and suggest that the structures below the Canterbury Plains have the ability to generate large earthquakes. Shallow seismic and GPR data were recorded just prior to the Canterbury Earthquake Sequence in the NW Canterbury Plains, the data were interpreted and shows interconnected faults and folds underlying an undisturbed surface (Carpentier et al., 2012).

Two recent studies were most beneficial to the research presented in this report. An intensive study of marine seismic data was done by Barnes et al. (2011) for the New Zealand Natural Hazards Research Platform, mapping horizons and fault structures beneath Pegasus Bay. The offshore seismic data and interpretations were used as a guide in interpreting the 2D seismic data collected in the city of Christchurch utilized in this research. The study by Jongens et al. (2012), which interprets faulting and folding of structures in seismic data from 1963 BP Shell Todd seismic reflection lines, Indo-Pacific Energy reconnaissance seismic reflection surveys, and existing nearby wells were referenced for interpretation of 2D seismic data acquired in the central Canterbury Plains.

### Earthquake history in the Canterbury Region

The Canterbury Plains are fairly quiet in terms of historical seismicity. Pettinga et al. (2001) summarized historical earthquakes in the Canterbury Plains, based on research from the New Zealand National Earthquake Information Database. The most significant historical earthquakes related to this study in the Canterbury region are the 1869 and 1870 Christchurch earthquakes, of approximate magnitude 5 and 5.5 respectively. Further west into the Canterbury Plains near the Darfield area, there are no records of large earthquakes (Gledhill et al., 2011).

## SEISMIC INTERPRETATION

### Data acquisition and processing

A collaborative effort between the University of Calgary CREWES research group and the University of Canterbury resulted in a 2D reflection seismic data program in April 2011. Seismic data was acquired in the city of Christchurch and the Canterbury area with the goal of mapping blind faults, and interpreting the structure of the Greendale Fault. The 2011 Christchurch seismic acquisition program parameters are given in Hall et al. (2011). A total of 6 seismic reflection lines were acquired; however the interpretation of just three lines will be included in this study. The 2D seismic data was processed by Sensor Geophysical Ltd. in Calgary, Alberta. Final post-stack migrated seismic sections are used for interpretation using the IHS Kingdom® Suite Interpretation Package.

**Christchurch seismic data**

Two 2D seismic lines were acquired in the city of Christchurch: Line 1 was acquired along the eastern edge of Christchurch down the length of New Brighton Beach, and Line 2 was acquired in Christchurch city center along Barbadoes Street. An overview map of the seismic line locations is shown in Figure 10.

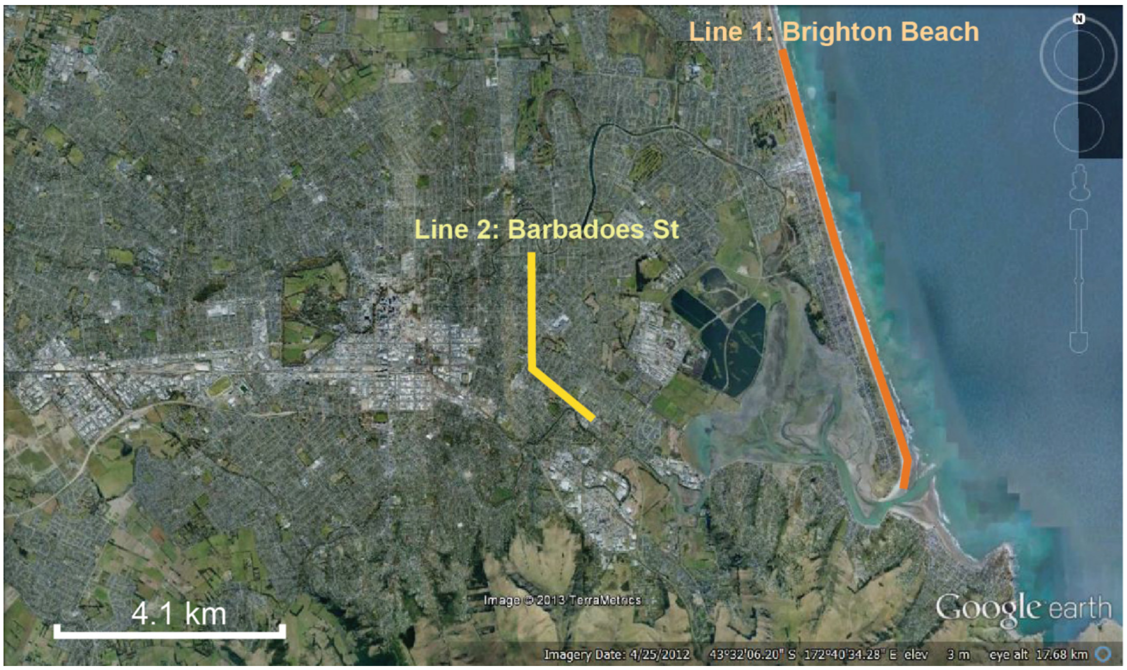



Figure 10. Overview map showing seismic data acquisition in the city of Christchurch, New Zealand. Line 1 (orange) is along New Brighton Beach, and Line 2 (yellow) is along Barbadoes Street. Google earth V 7.0.3.8542. (25 April 2012) Christchurch, New Zealand. 43°32’06.48”S, 172°40’34.28”E, Eye alt 17.68 km. TerraMetrics 2013. http://www.earth.google.com [May 30, 2013].

*Seismic interpretation of Line 1, New Brighton Beach*

The New Brighton Beach seismic line is 8 km long, and spans from stations 101-900 with 10 m shot and receiver spacing. Figure 11 shows a map of the seismic line and corresponding stations, with an orange dashed line indicating the projected Port Hills Fault, extended to the surface (based on the slip model derived by GPS and DInSAR data in Beaven et al., 2012). The fault projection shows that the Port Hills Fault can be expected to intersect the seismic line near station 510. Approximately 1 km to the west of the northern portion of the seismic line is the Environment Canterbury Bexley testbore (well no. M35/6038), a 433 m deep testbore. The Bexley testbore is projected orthogonally to the seismic line to intersect it at station 715. Also used to provide information and considered in the interpretation of the acquired Christchurch seismic data are south trending high resolution marine seismic profiles in Pegasus Bay, parallel with seismic lines ranging from approximately 2 to 25 km to the east of the New Brighton Beach seismic profile (Barnes et al., 2011).


Figure 11. New Brighton Beach seismic line with corresponding stations is shown along the east coast of Christchurch. The Environment Canterbury Bexley testbore location is illustrated by the green star. The projection of the Port Hills Fault to the surface is shown by a dashed orange line and is based on GPS and DInSAR data from Beaven et al. (2012). Figure adapted from Hall et al. (2011). Google earth V 6.0.3.2197. (2011) Christchurch, New Zealand. 43°30’04.99”S, 172°48’32.49”E, Eye alt 10.89 km. TerraMetrics 2011, Whereis® Sensis Pty Ltd, and Geoeye 2011. http://www.earth.google.com [Oct 17, 2011].

The New Brighton Beach seismic profile without and with interpretation is shown in Figures 12a and 12b respectively. The top of the Late Quaternary Wainoni Gravels is identified with a green horizon marker near 250 ms (Figure 12b). The RMS seismic P-wave velocity in the top 300 ms is approximately 1680 m/s. The Wainoni Gravels were deposited as outwash deposits from glacial periods and has no outcrop, so its lateral extent is uncertain (Brown et al., 1988). The Wainoni gravels present an acoustic impedance contrast from the overlying formations which contain more sand and clay, whereas the Wainoni gravels contain coarser gravel. However, the Wainoni gravels are difficult to distinguish from the continuous sequence of overlying fluvial deposits, even in a wellbore (Brown et al., 1988). The depth to the Wainoni gravels at station 715 is calculated to be approximately 150 m deep, which is in close agreement with the depth to Wainoni gravels formation provided in Brown et al. (1988) and the Bexley testbore. The maximum thickness of the Wainoni gravels are approximately 20 m (Brown et al., 1988).

The Early Pleistocene Top Kowai Formation is identified in the Bexley testbore just below 240 m and also in the Barnes et al. (2011) study. The Top Kowai Formation is interpreted as the yellow horizon marker. The Kowai Formation thins towards the south and Banks Peninsula which consists of large overlapping remnant composite volcanoes (Forsyth et al., 2008), where the Miocene Volcaniclastics are encountered.

The Banks Peninsula Miocene Volcaniclastics (6 to 9 Ma) are interpreted with a red horizon marker along a hummocky reflector, and have a strong and continuous seismic reflector that marks the hydrologic basement (Finnemore, 2004). The Miocene Volcaniclastics outcrop near the southern end of the seismic line along coastal cliffs of Banks Peninsula (Barnes et al., 2011). RMS seismic velocities of the volcanics are approaching approximately 1900 m/s, while the interval velocities are approximately 2700 m/s at station 520. Barnes et al. (2011) show interval velocities of 2500-2700 m/s for the Miocene Volcanics.

The south dipping Port Hills Fault projects approximately 350 m below the ground surface near station 510 (for a velocity of 1800 m/s at 0.44 s). Beaven et al. (2012) modeled maximum slip of 2.5 m at 5-6 km depths in the Christchurch earthquake. The horizon marker for the Miocene Volcanics shows vertical displacement of approximately 27 ms, or 28 m for a material velocity of 2080 m/s. The larger calculated vertical displacement in this study indicates that most of the displacement occurred pre-Upper Miocene. A possible projected fault is also indicated on the northern end of the seismic line below station 760, and just encounters the Miocene Volcaniclastics. Deformation and up-warping of seismic reflections is also seen between stations 700 to 800 near the surface. Most other geologic structure at greater depths in the seismic reflection survey is concealed below the Miocene Volcanics.

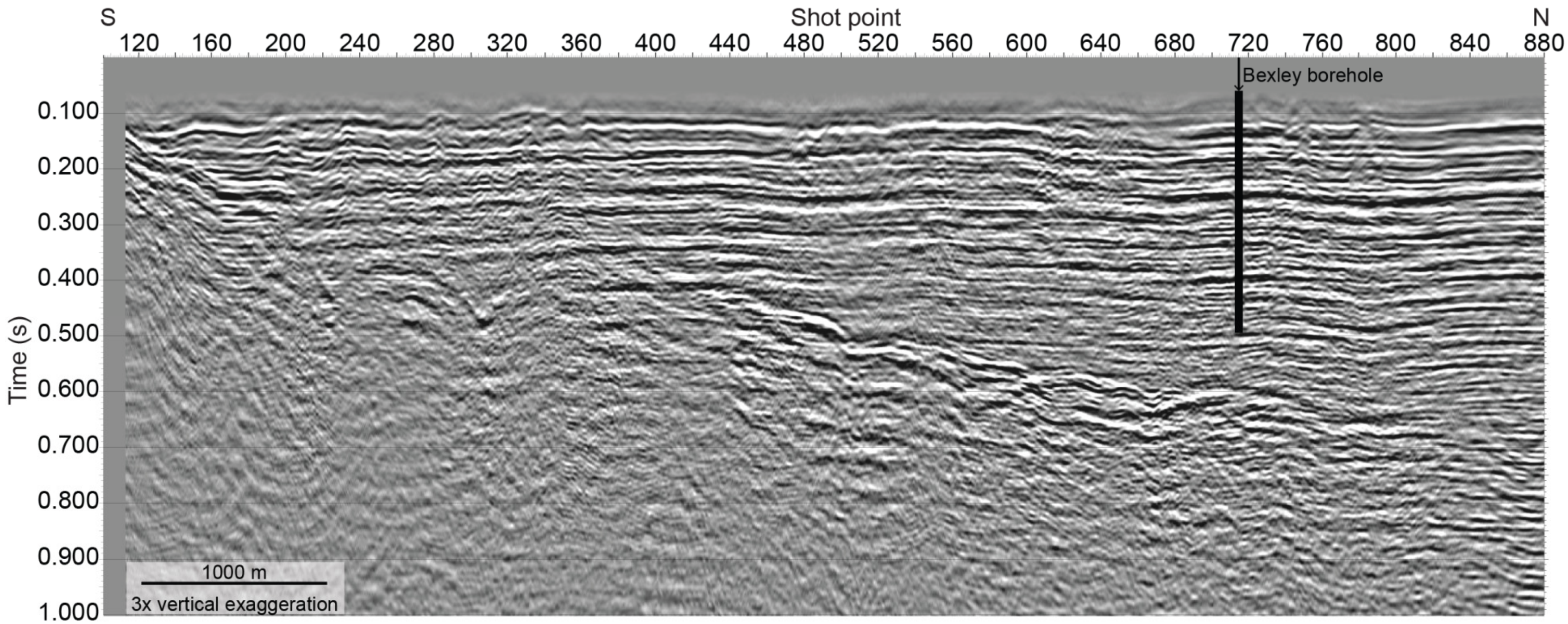



Figure 12a. Uninterpreted New Brighton Beach 2D seismic line with 3x vertical exaggeration. The Bexley testbore is 1 km to the west of New Brighton Beach, and the borehole location is projected onto the seismic line.

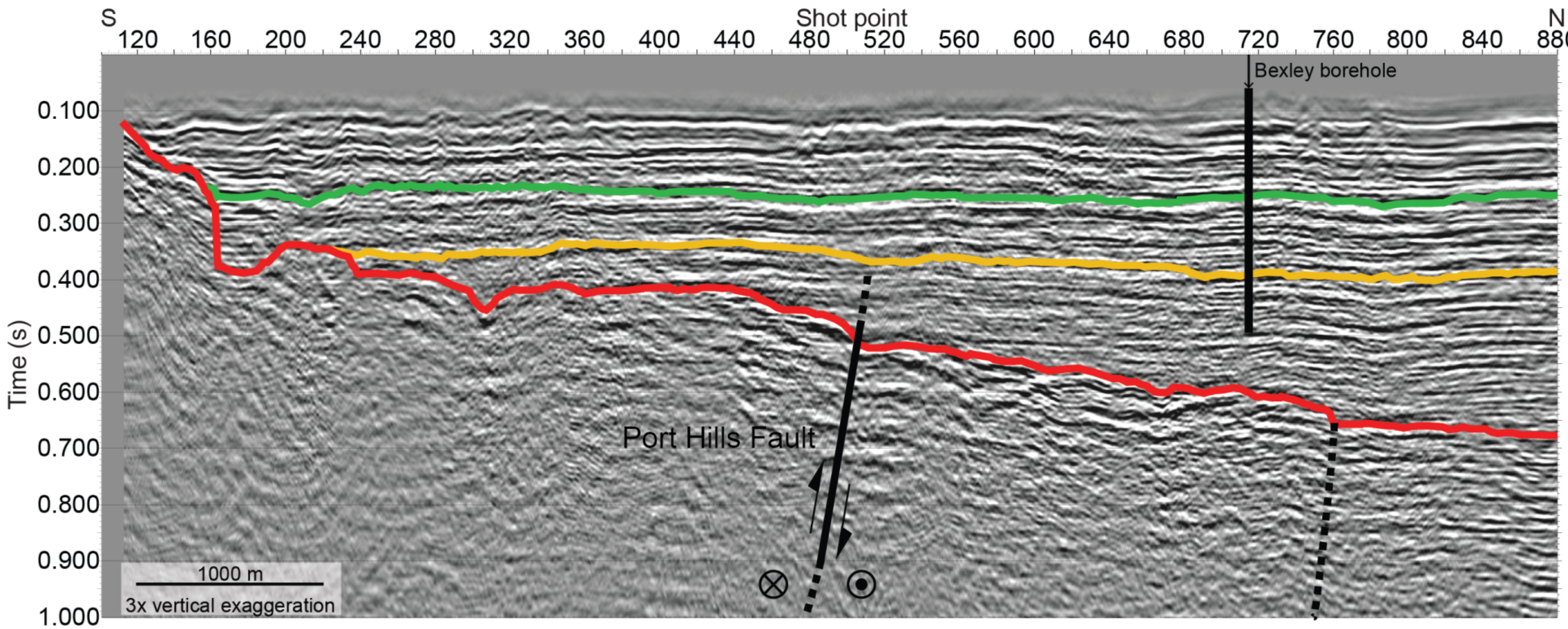



Figure 12b. Interpreted New Brighton Beach 2D seismic line with 3x vertical exaggeration. The green horizon represents the Wainoni gravels, the yellow horizon represents the Early Pleistocene Top of Kowai Formation, and the red horizon represents the Miocene Volcaniclastics. The Port Hills Fault is interpreted 400 ms below stations 500-520. An additional projected fault shown in black dashed line towards the north end of the seismic line just intersects the Miocene Volcaniclastics.

*Seismic interpretation of Line 2, Barbadoes Street*

The 3.7 km long Barbadoes Street seismic line (Figure 13) was acquired through Christchurch city center and is just less than 8 km west of New Brighton Beach. The line started at the south with a NW trend, then turned north onto Barbadoes Street. Acquisition parameters are described in Hall et al. (2011). Considering the GPS and DInSAR modelled data (Beaven et al., 2012); the Port Hills Fault is not expected to be seen in this seismic line data.


Figure 13. Barbadoes Street seismic line (in blue). Started on south end at station 205 and ended north at station 571. Google earth V 7.0.3.8542. (25 April 2012) Christchurch, New Zealand. 43°32’06.98”S, 172°40’34.27”E, Eye alt 10.24 km. Whereis® Sensis Pty Ltd. and TerraMetrics 2013. http://www.earth.google.com [June 7, 2013].

The Barbadoes Street seismic profile without and with interpretation is shown in Figures 14a and 14b respectively. The change in line direction occurs at station 360. In the shallow section of the survey, a possible infilled channel is identified in blue. Also, the disruption in the near-surface between stations 525-545 may indicate a liquefied zone. The top of the Late Quaternary Wainoni Gravels is identified with a green horizon marker slightly above 250 ms at a depth of 165 m (Figure 14b). The Top Kowai Formation is interpreted with a yellow horizon marker near 375 ms, and intersects the Miocene Volcaniclastics at the southern portion of the line, indicated by a red horizon marker. Two possible south dipping faults are indicated in the deeper part of the seismic section.

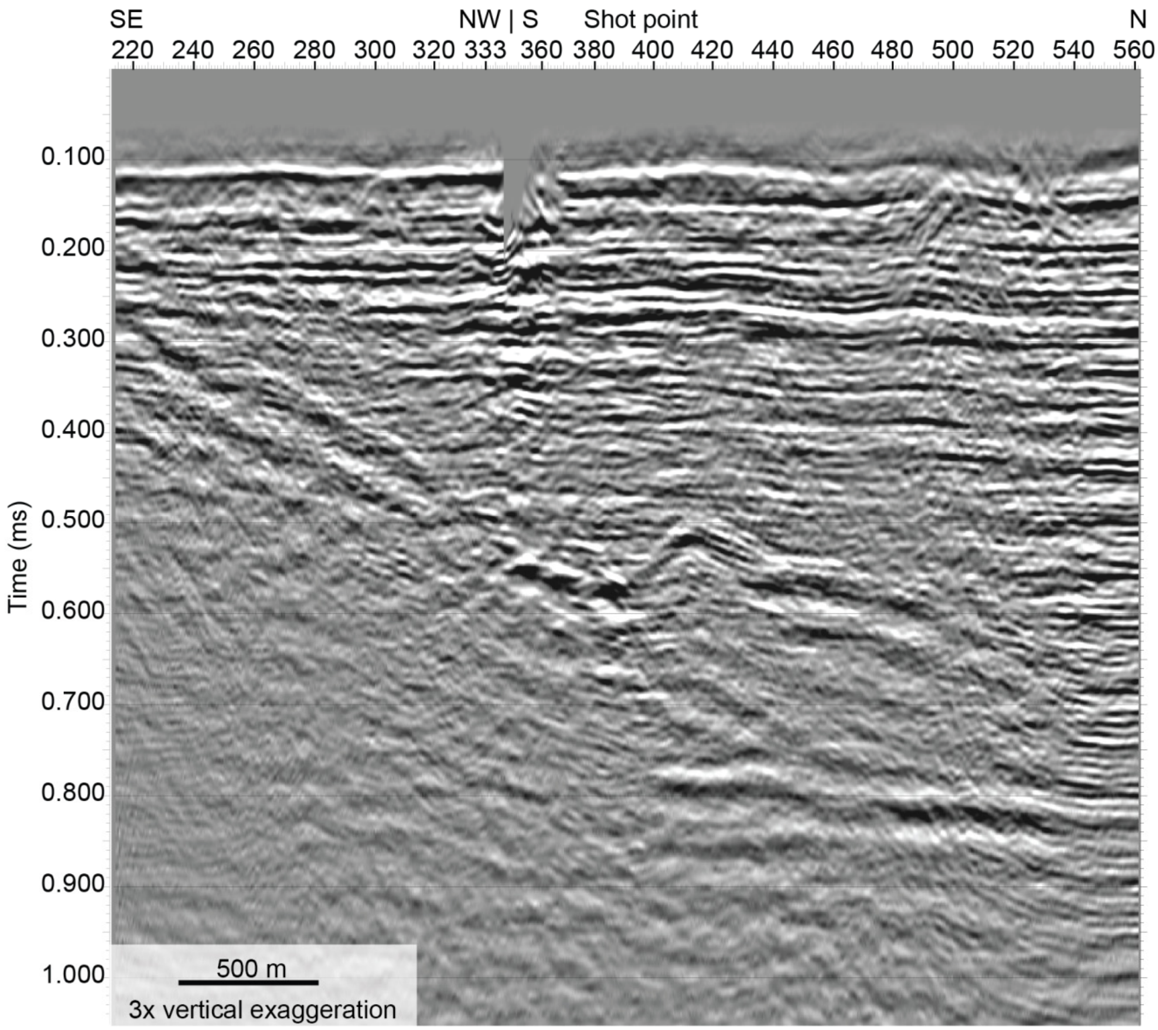



Figure 14a. Barbadoes Street seismic profile without interpretation, 3x vertical exaggeration.

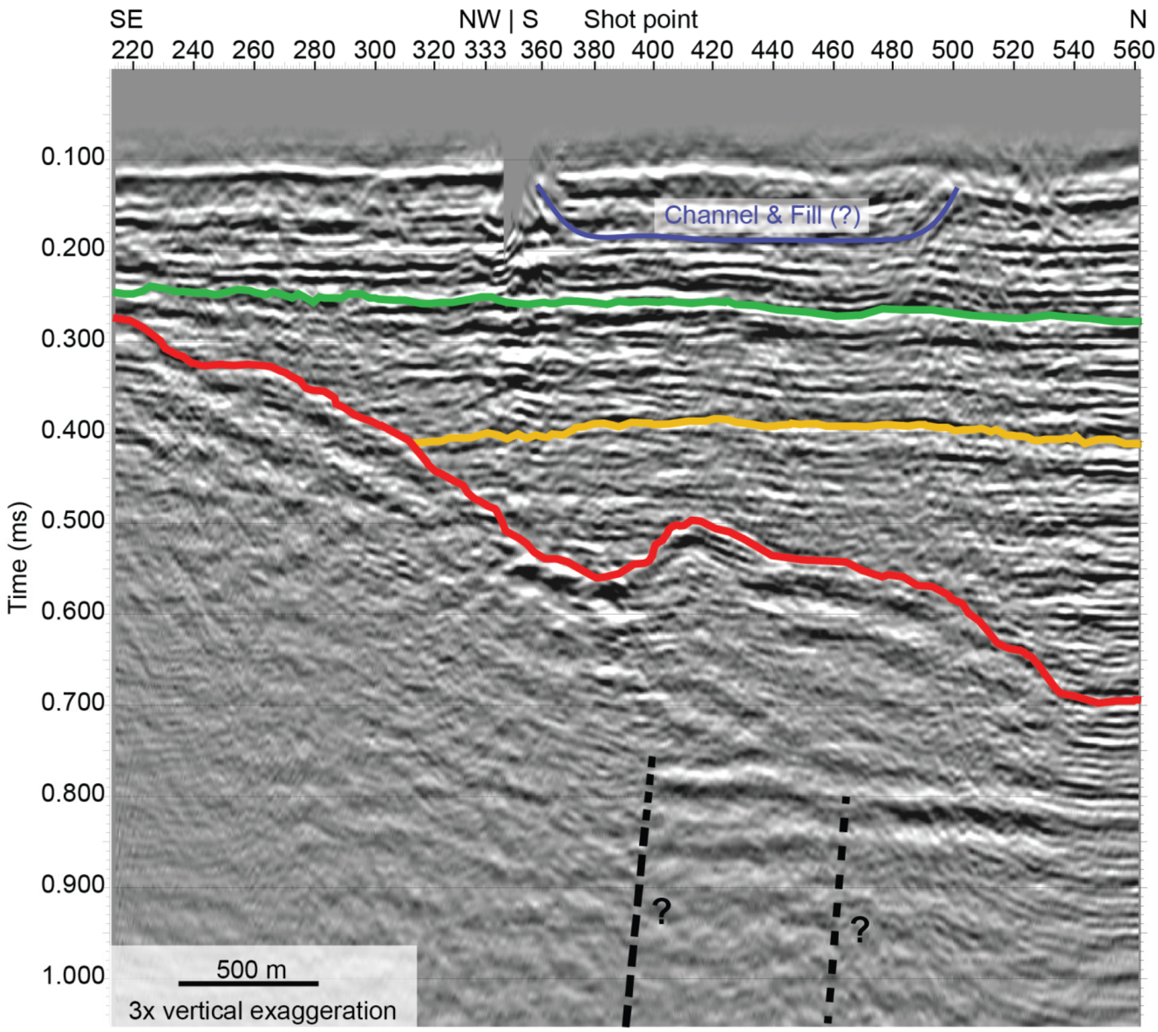



Figure 14b. Barbadoes Street seismic profile with interpretation, 3x vertical exaggeration. The green horizon represents the Wainoni gravels, the yellow horizon represents the Early Pleistocene Top of Kowai Formation, and the red horizon represents the Miocene Volcaniclastics. Possible projected faults are indicated in dashed black lines. Also interpreted is a channel and fill zone in the near surface.

*Seismic interpretation of Line 3, Highfield Road*

The Highfield Road seismic line (Figure 15) is approximately 35 km west of Christchurch city center, and intersects the EW trending Greendale Fault near station 440. The seismic line acquired on Highfield Road runs from south to north and is 3.4 km long. Data acquisition parameters are summarized in Hall et al. (2011). The fault and fold structures beneath the Canterbury plains to the west of Highfield Road interpreted by Jongens et al. (2012) were considered during the interpretation of this seismic line.

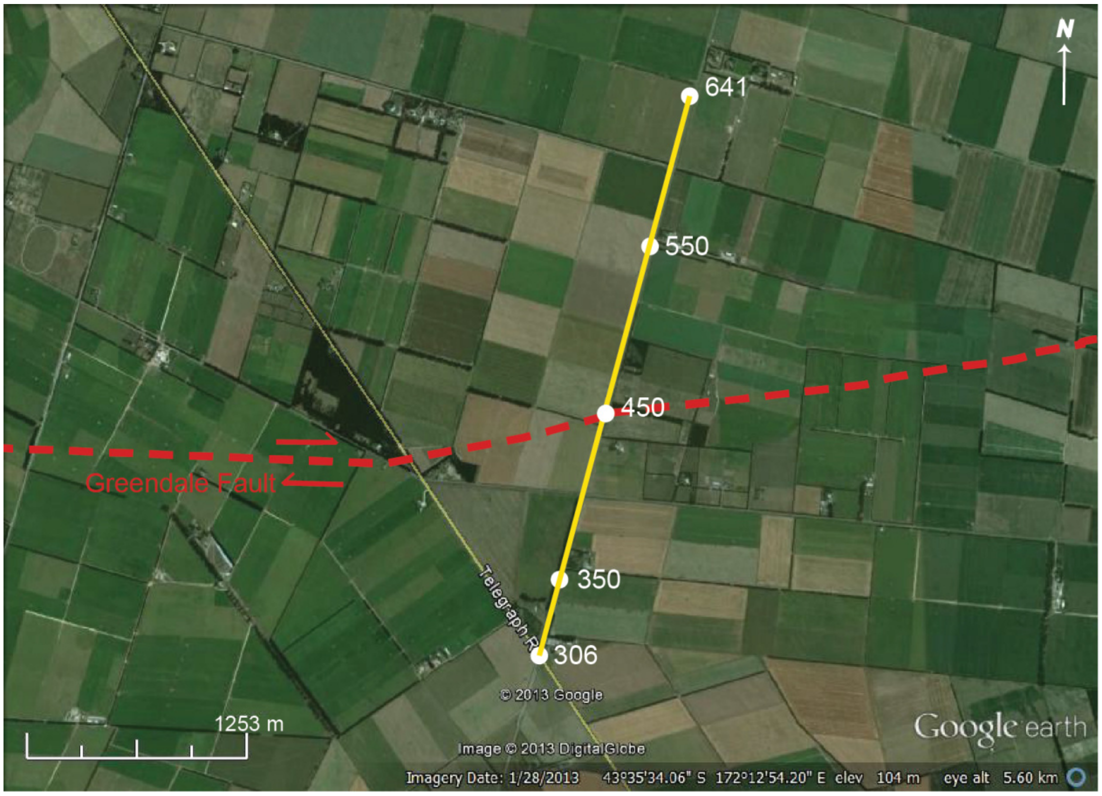



Figure 15. Highfield Road seismic line (in yellow). Started on south end at station 306 and ended north at station 641. The Greendale Fault ruptures the surface in an E-W orientation. Greendale Fault trace based on Holden et al. (2011). Google earth V 7.0.3.8542. (28 January 2013) Highfield Road, New Zealand. 43°35’34.06”S, 172°12’54.20”E, Eye alt 5.6 km. DigitalGlobe 2013. http://www.earth.google.com [June 29, 2013].

Figures 16a and 16b show the uninterpreted and interpreted seismic data respectively. The 125,000 year gravels, an inter-fingering of river gravels with coastal sand, silt, clay, and peat from the last glacial-interglacial cycle (Brackley, 2012) is marked by a light blue horizon pick along a prominent reflector. The 125,000 year gravels mark high eustatic sea levels during the last interglaciation (Bal, 1996) when temperatures were warmer. Slip displacement is difficult to calculate in the shallow unconsolidated materials, however approximately 7 m of vertical deformation (assuming an interval velocity of 2400 m/s for 6 ms of time difference) exists along this horizon.

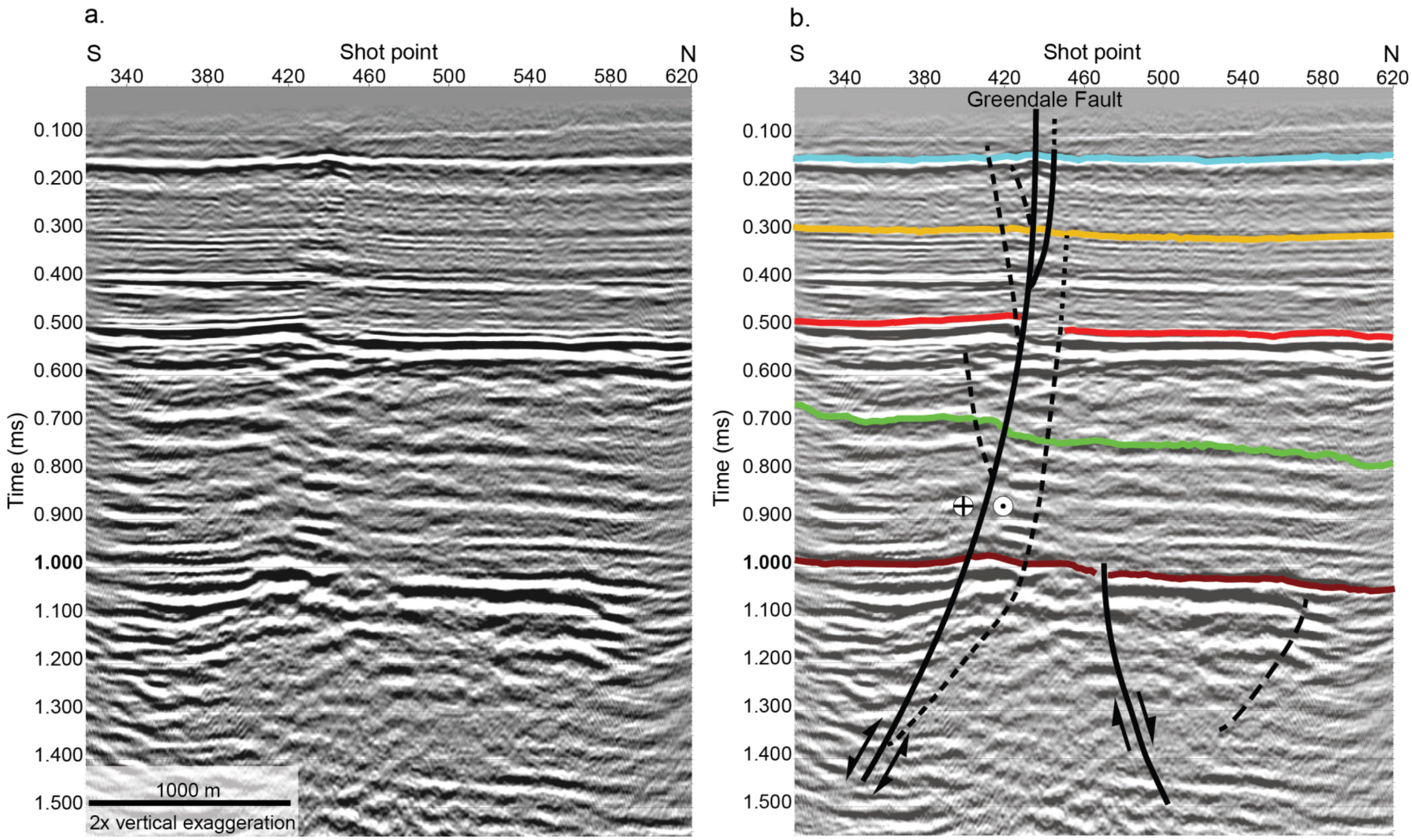



Figure 16. (a) Highfield Road seismic line uninterpreted. (b) With interpretation. The 125,000 year gravels are represented by the light blue horizon, the Top of the Kowai formation is represented by the yellow horizon, the Miocene volcaniclastics/Mid-Tertiary limestone is represented by the red horizon, the Top of the Paleogene (?) is represented in green, and the undifferentiated Mesozoic basement is picked in brown. The Greendale fault is illustrated below station 440, where the fault ruptured the surface.

The Pliocene-Plesitocene Kowai Formation is interpreted by the yellow horizon near 300 ms. Vertical displacement is calculated to be approximately 17 m from a 13 ms time difference in the horizon marker 600 m on each side of the fault, assuming an interval velocity of 2600 m/s.

The Miocene volcaniclastic horizon marker is interpreted near 500 ms in red, or it possibly could also be interpreted as a Mid-Tertiary limestone. Vertical displacement is much more prominent at this reflector and approximately 26 m of displacement is calculated from the vertical time difference of 20 ms at the horizon 1 km on each side of the fault, assuming an interval velocity of 2600 m/s.

The Top of the Paleogene, representing marine sediments and volcanic deposits during regional submergence and marine transgression (Forsyth et al., 2008) is speculated to be the green horizon marker interpreted near 750 ms. The Top of the Palogene shows the most horizon offset (47 ms) on each side of the fault, with displacement of over 50 m for an assumed interval velocity of 2300 m/s.

The lowermost brown reflection marker is interpreted to be the top of the undifferentiated Mesozoic basement. Approximately 38 m of displacement offset is calculated on each side of the fault (time difference of 32 ms) for an interval velocity of 2400 m/s. The basement rock surface is approximately 1165 m deep.

The Greendale Fault is shown to rupture the surface. Several fault splays are also interpreted off the main Greendale Fault. The strike slip motion of the fault is indicated by towards and away arrows, with the foot wall on the north side of the fault displaced to the east, and the hanging wall on the south side of the fault displaced towards the west. A blind fault structure is interpreted to the north of the Greendale Fault, and is interpreted to be not reverse-reactivated. Further north below the basement, another possible fault is projected and indicated by a dashed line.

## Discussion on fault reactivation

The faults in this study are comparable to south dipping E-W trending faults observed in Pegasus Bay (Barnes, 2011) and the southern Canterbury Plains (Jongens et al., 2012). Barnes identifies two types of basement involved faults: Cretaceous and Paleogene inactive extensional structures, and basement faults that have undergone Plio-Pleistocene contractional and strike slip deformation. Most Plio-Pleistocene faults are considered reactivated Cretaceous and Paleogene structures which are predominantly E-W trending. It is highly probable that the Greendale Fault is associated with a reactivated Late Cretaceous normal fault (Jongens et al., 2012).

Barnes et al. (2011) infer that S-SE striking offshore faults have considerable strike-slip displacement, and more NE striking faults are more likely to have oblique-slip displacement, which is in agreement with the described structure of the Greendale and Port Hills faults, respectively.

## CONCLUSIONS AND RECOMENDATIONS FOR FURTHER WORK

The interpretation of P-wave reflection seismic data shows the presence of faults in the Canterbury Plains, previously suspected in the area, but never mapped. The faults have complex structures, and have the potential to reactivate under current tectonic stresses (Barnes et al., 2011). Seismic interpretation of the 2D seismic reflection data in the city of Christchurch identified the Port Hills Fault in the New Brighton Beach seismic profile, which projects approximately 350 m below surface. Displacement along the Miocene horizon shows approximately 28 m of slip. An additional blind fault was interpreted to occur further north of the Port Hills Fault and may also be a reactivated reverse fault. The seismic profile along Barbadoes Street in the city center of Christchurch is relatively quiet in terms of active faults. However, a possible infilled channel was identified in the near surface, as well as an area possibly disturbed by liquefaction. The Highfield Road seismic section provided a comprehensive subsurface image of the complexity of the Greendale Fault, which was crossed by the seismic profile. Several fault splays were identified off the main fault, as well as a north dipping normal fault, that may not have been reactivated.

The 2D seismic reflection profiles acquired in the Canterbury Plains of New Zealand was of good quality and used for geologic interpretation in this research. However to better characterize faults with complex structure, which is a three dimensional problem, a high resolution 3D seismic survey is recommended. Success has been shown in imaging active faults zones using 3D seismic in New Zealand (Kaiser et al., 2011).

The geologic interpretations of this research were based on comprehension of the geologic history of the Canterbury Plains, previous geophysical seismic interpretations both offshore and on land, and the 433 m deep Bexley wellbore. Deep wellbores within the city of Christchurch, and closer to the Greendale Fault would help constrain the seismic interpretations.

In addition, integrated geophysical, geologic, and engineering studies are recommended for future monitoring of the region.

## ACKNOWLEDGEMENTS

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