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EARTHQUAKE OF 21 FEBRUARY 2011 IN NEW ZEALAND
Generation of Glacial Tsunami

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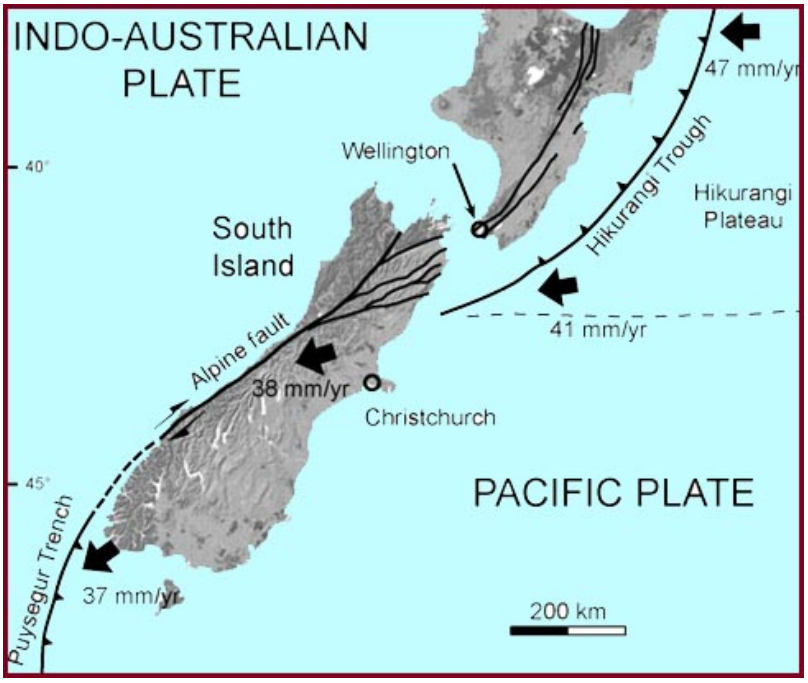
ABSTRACT

An earthquake with Richter magnitude 6.3 struck in the vicinity of Christchurch in New Zealand. It was the second largest seismic event to strike the area within a short time interval. Although of relatively small magnitude, the quake was extremely destructive as it struck much closer to the city than the previous earthquake of 4 September 2010. More than 180 people lost their lives. The earthquake occurred onshore, so there was no tsunami generated. Loss of power at the tide gauge of Lyttelton Port of Christchurch failed to record any wave activity. The GeoNet site at Sumner Head, which is located on the open coast, registered some longer period waves, but these were the result of weather related generation and not of seismic origin. According to eyewitnesses, the earthquake's motions were mild in Aoraki Mt. Cook National Park on the western side of New Zealand's South Island, but the shaking triggered an icefall off the end of the Tasman Glacier's lake and generated significant tsunami waves with an initial wall of water that was 50 or 60 meters high, but up to 3.5 meters high along its shores. The present study assesses the tectonic stresses and seismicity of the Marlborough fault system along the northern part of South Island, and briefly evaluates the potential of future tsunami generation from earthquakes that may be generated near New Zealand's Hikurangi Trough, that may also impact the coasts of South Island as well as the coastlines near the City of Wellington on North Island.

Keywords: *New Zealand earthquakes; glacial tsunami; Christchurch; Wellington; Canterbury area; Hikurangi Trough; Marlborough fault system; Alpine Fault; Puysegur Trench; Tasman Glacier lake.*

1. INTRODUCTION

A shallow focus earthquake occurred on 21 Feb 2011, (UTC 12:51, 22 Feb 2011 NZDT local time and date) at the Canterbury Plains near the city of Christchurch, the largest city of South Island of New Zealand. The seismic region where this earthquake occurred includes the southwest part of South Island (known as Fiordland) and extends offshore to the southwest covering the adjacent Puysegur Trench, which marks the tectonic boundary where the Pacific and Australian plates collide (Pararas-Carayannis, G. 2016 a, b).



Although the earthquake's magnitude was only 6.3, it was extremely destructive to the city of Christchurch. The earthquake had a shallow rupture and its focal mechanism indicated that it was mainly a strike-slip event. Five months earlier, in September 2010, a stronger earthquake had struck 40 kms west of Christchurch, near the town of Darfield, but did not cause significant damage.

Fig 1. Map of the Indo-Australian plate and of major faults, trenches and troughs, as well as the directions and rates of tectonic movements

No open coast tsunami was generated, but the strong ground motions triggered a significant icefall (a glacial tsunami) off the end of the Tasman Glacier's lake which generated significant waves along its shores. A subsequent study examines the potential of tsunami generation from earthquakes occurring near the Macquarie Fault and Alpine fault zones, the Puysenguir Trench, the Marlborough fault system, the North Island fault system, the Hikurangi Trough of the lower Kermadec Trench (Fig 1, 2). Additionally, prehistoric tsunamis from cascading nuée ardentes and pyroclastic volcanic flows into the Bay of Plenty on the North Island and elsewhere in New Zealand will be examined.

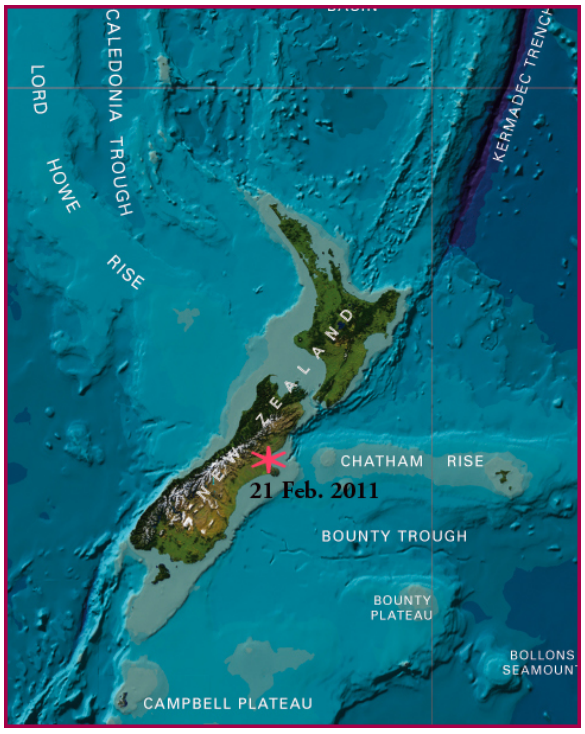
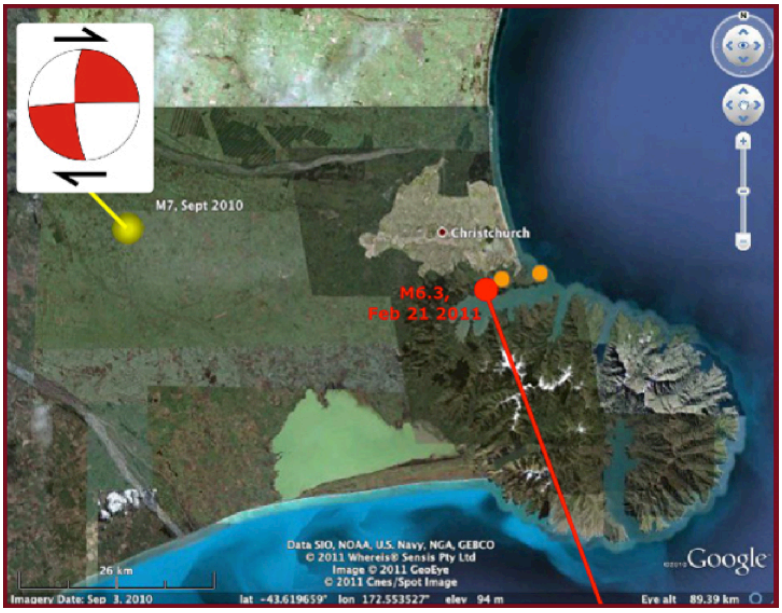


Fig 2. Epicenter of the 21 February 2011 Earthquake



2. THE EARTHQUAKE OF 21 FEBRUARY 2011

Date, Time, Epicenter, Magnitude and Rupture - The earthquake had moment magnitude M_w 6.2 (M_L 6.3). It occurred at 23:51 on 21 February 2011 UTC (12:51, 22 Feb 2011 NZDT local time and date). Its epicenter (Fig. 2 & 3) was at the Canterbury Plains about 6.7 km from the center of Christchurch, New Zealand - the largest city of South Island, which is over 100 Kms from the Alpine fault.

Fig 3. Epicenters of the M7 4 September 2010 and of the M6.3 21 February 2011 earthquakes near Christchurch (NOAA graphic)

Its shallow rupture and its focal mechanism indicated that it was mainly a shallow, strike-slip event. The earthquake was felt across the South Island and parts of the lower and central North Island.

The seismic region where this earthquake occurred includes the Southwest part of South Island (known as Fiordland) and extends offshore to the Southwest covering the adjacent Puysegur Trench, which marks the tectonic boundary where the Pacific and Australian plates collide (Fig. 1).

Aftershocks - There were many strong aftershocks following the main earthquake. Two strong aftershocks occurred on Monday, 14 June 2011, nearly four months after the 21 February 2011 main quake. According to USGS data, the first was a shallow event with depth of 11 km and had magnitude of 5.2 and epicenter about 9 km (5 miles) east-southeast of the main event. A second quake occurred 90 minutes later. It was also shallow (focal depth 9 km) and had a Richter magnitude 6.0. Its epicenter was — about 13 kilometers (8 miles) north-northeast of Christchurch (Fig. 3).

Loss of Life and Damages - There was severe destruction to the city of Christchurch. It was particularly damaging because it was a shallow quake near a densely populated area. The strong ground motions caused the collapse of the Canterbury Television building killing 115 people. Significant liquefaction affected the eastern suburbs, producing around 400,000 tonnes of silt.

Remaining Seismic Stress in the Christchurch Region After the Earthquake - The earthquake of 22 February 2011 near Christchurch, did not appear to have released all its energy (Pararas-Carayannis, G. 2016 a, b). Also, it raised the question on whether it occurred on a new fault or along a previously Un-recognized fault — an offshoot from the Alpine fault — that did not rupture in recent geologic times and thus there was no historic data. Although the earthquake of 22 February 2011 had a moderate magnitude of 6.3, and tremors lasted for only ten-seconds, what made it worse was the fact that it occurred close to the city of Christchurch where buildings had been weakened — and not subsequently upgraded — by an earlier 7.1 event of 4 September 2010 in the region (Fig 3).

Also, the 22 February 2011 quake and a subsequent event on 24 July 2016 - both near Christchurch - raised the question on whether all accumulated stress in the region was released, or whether additional quakes could be expected. The progression of subsequent earthquakes in the region, indicated that energy was transferred to adjacent faults — as indeed it happened in 2016 (Pararas-Carayannis, 2016 a, b). More earthquakes with local tsunamigenic potential were expected near South Island with additional adverse impact in the Christchurch and in the Wellington area of North Island. Several of the active faults that may be present in this region have not been adequately identified.

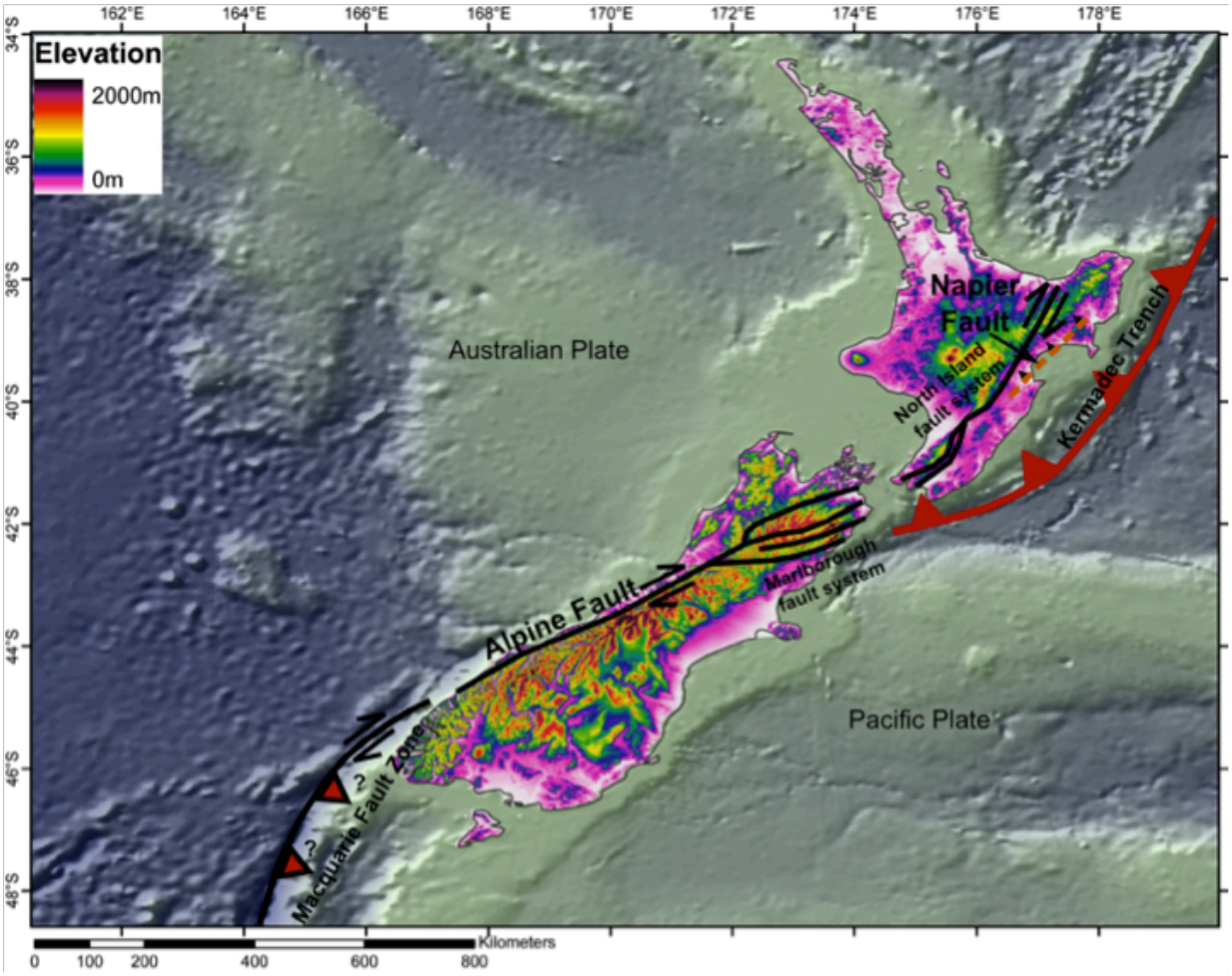


Fig 4. The Macquarie Fault and Alpine fault zones, the Puysenguir Trench, the Marlborough fault system, the North Island fault system, the Hikurangi Trough of the lower Kermadec Trench.

Subsequently, on 1 September 2016, a magnitude 7.2 earthquake occurred off the East coast of North Island. However this quake had a deep focal depth of 99 miles, thus did not pose a threat of tsunami generation or of damage from surface seismic waves. Based on assessment of tectonic stresses, the present study postulated that subsequent major earthquakes in the region could occur that could also impact the capital city of Wellington. The following section provides a brief review of some of the major and large

earthquakes that have occurred in New Zealand in relatively recent times — some generating destructive tsunamis. As previously stated a subsequent study in preparation examines the potential of tsunami generation from earthquakes occurring near the Macquarie Fault and Alpine fault zones, the Puysenguir Trench, the Marlborough fault system, the North Island fault system, the Hikurangi Trough of the lower Kermadec Trench (Fig. 1, 4) — as well as prehistoric tsunamis from volcanic sources.

3. PREVIOUS AND SUBSEQUENT LARGE EARTHQUAKES IN NEW ZEALAND - A Brief Review.

Given the nature of the geology, earthquakes in New Zealand along the tectonic boundary where the Pacific and Australian plates collide are common, although those of magnitude 7.0 or more are relatively infrequent. A list of large earthquakes which have occurred in New Zealand is provided by Wikipedia (https://en.wikipedia.org/wiki/List_of_earthquakes_in_New_Zealand). Only earthquakes with a magnitude of 6.0 or greater are listed, except for a few that had a moderate or severe impact. Aftershocks are not included, unless they were of great significance or contributed to a death toll, as that of the 2011 Christchurch earthquake discussed in this paper.

3a. Large Historical Earthquakes and Tsunamis - The largest recorded earthquake in New Zealand took place in 1855 at Wairapa and had a magnitude of 8.2. Earthquakes of 7.8 magnitude have caused significant damage and some loss of life in 1848, 1929 and 1931. The major earthquakes that affected the broader region of Canterbury Province occurred in 1888 and in 1929. In more recent times, the same Canterbury area has been impacted by earthquakes of M5.9 and M6.7 in 1994 (USGS; GeoNet; Pararas-Carayannis, 2016 a, b). In July 2009 an earthquake of M7.8 occurred in the South Island's relatively uninhabited west coast region. The next section reviews briefly only the more recent larger earthquake events - some having generated tsunamis.

1931- FEBRUARY - 3 - The "Napier earthquake" of 3 February 1931 was the worse natural disaster in New Zealand. It caused many deaths, injured thousands of people and caused severe destruction, not only in the Hawke's Bay Region of North Island but on South Island as well. According to a 1931 *New Zealand Listener* article, this quake resulted in 258 deaths, which included two missing people - presumed dead. The epicenter of the 1931 quake was about 15 km north of the town of Napier. Its magnitude was estimated at 7.8 M_s (moment magnitude 7.9 M_w), and the ground motions lasted for two and a half minutes. The quake was a strike-slip event (Mouslopoulou et.al, 2007; Pararas-Carayannis, 2016 a, b). There were 525 aftershocks recorded in the following two weeks, with 597 being recorded by the end of February 1931. The main shock and many of the aftershocks were felt throughout New Zealand, and according to GeoNet as far south as Timaru, on the East coast of South Island.

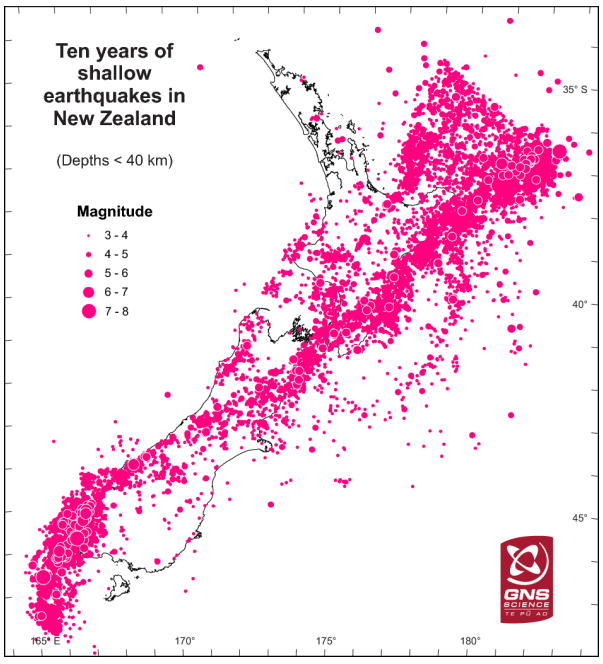
1979 - OCTOBER 12 - A thrust earthquake with magnitude 7.3 occurred offshore near the Puysegur Trench to the southwest of South Island.

2003 - AUGUST 21- This was a shallow earthquake which occurred in Fiordland - a remote seismically active region in the southwest of the South Island. It was a thrust event had a moment magnitude M_w7.2 . the largest to occur in New Zealand in 35 years (Reyners, et.al., 2003; McGinty, 2003).

2004 - NOVEMBER 22 - This earthquake occurred off the West coast of South Island on 22 November 2004 at 20:26:23 UTC and had a magnitude 7.1 and a relatively shallow depth (NEIC). No tsunami was generated.

2010 - SEPTEMBER 4 - A severe earthquake - subsequently named as the Canterbury earthquake of 2010 - struck near the city of Christchurch, at the South Island. No fatalities were reported for this quake but there was considerable damage to buildings in and around Christchurch. It appears that the origin of this quake was along one of the two major faults, the Hope Fault and the Alpine Faults, which run along the South Island and are the main expression of the boundary between the Pacific and Indian (or Indo-Australian) tectonic plates (Pararas-Carayannis, 2016 a, b). The Richer magnitude of this event was estimated as M7.0 (USGS)(also reported locally as 7.1) - making it one of the strongest in 2010. The USGS reported that it was lateral (strike-slip) movement that caused it (Fig 3). The epicenter was between 40-50 km west Christchurch (sources vary) and was followed by numerous aftershocks for a period of days and weeks. At least thirty of these aftershocks had magnitudes of at least M4.0. There was a strong tremor of M5.1 on 8 September 2010 and another one of M5.0 on 19 October 2010. However, the October event was too strong and too far in space and time to be considered as an aftershock.

2016 - NOVEMBER - 14 - This event known as the 2016 Kaikoura earthquake, had a moment magnitude 7.8 (M_w) (US Geological Survey, 2016; GeoNet, 2016). It occurred on 14 November 2016 NZDT (11:02 on 13 November UTC) near the towns of Culverden and Kaikoura, and about 95 km from Christchurch. Its focal depth was about 15 kms and it was accompanied by several sequences of ruptures on numerous faults on land and at sea (GeoNet, 2017). The ground motions lasted for about two minutes. Tsunami waves up to 7 meters were documented at Goose Bay. Some other tide gauges that recorded the tsunami waves were in Wellington Harbor, Castlepoint, Christchurch, and the Chatham Islands (Daly, M., 2017) https://en.wikipedia.org/wiki/2016_Kaikoura_earthquake



4. SEISMICITY OF NEW ZEALAND - A Brief Review

Active tectonic processes in New Zealand result in thousands of earthquakes every year (Fig 5). However, most of the quakes are too small to be felt and cause no damage.

Fig 5. Distribution of shallow focus earthquakes in New Zealand over a ten year period (source GNS Science).

New Zealand's high frequency of usually small quakes results from its proximity to the broad boundaries where

the tectonic plates of the Pacific and Australian plates collide. North Island is part of the Australian continental plate which is under-thrust by the higher density Pacific Oceanic plate along a zone of subduction. Something similar is occurring south-west of the South Island of New Zealand where sliver of continental crust lies on the Pacific plate, and it is the Australian plate that is being destroyed through subduction (Pararas-Carayannis, 2016 a, b).

In between, the continental crust on the Pacific and Australian plates slide past one another on South Island, creating a conservative plate margin where crust is neither created nor destroyed. This area is still prone to earthquakes, most notably along the Alpine fault to the west of South Island. Further away from these fault zones the ground is generally more quiescent. The historical record indicates that in the last 200 years both North and South Islands of New Zealand have experienced several earthquakes with magnitudes greater than 5, but few of greater magnitudes.

5. GENERATION OF GLACIAL TSUNAMI

The earthquake occurred onshore, so there was no open coast tsunami generated. The Loss of power at the tide gauge of Lyttelton Port of Christchurch failed to record any wave activity. The GeoNet site at Sumner Head, which is located on the open coast, registered some longer period waves but these were the result of weather related generation and not of seismic origin.

The earthquake's ground motions were mild at the Aoraki Mt. Cook National Park on the western side of New Zealand's South Island. However, according to eye-witnesses, the shaking triggered a break of an iceberg off the end of the Tasman Glacier Lake and generated a tsunami (Fig 6).

Fig 6. Photo of iceberg in Tasman Lake at Aoraki Mt. Cook National Park (photo from Glacier Explorers)

The glacier shown in Fig. 6 is similar to the iceberg that calved and collapsed into the Tasman Lake in the Aoraki Mt. Cook National Park right after the earthquake. According to eyewitnesses reports the initial wall of water was 50 to 60 meters in height and boats in the lake experienced big waves for about 30 minutes and that these waves were up to 3.5 meters in height. Subsequent estimates that were provided, mentioned that about 30 million tonnes of ice calved across 1200 meters of the glacier's face. According to the same estimates the glacier's top was 30 meters above the surface of the lake and more than 250 meters below the surface to the bottom of the lake, and its thickness was estimated to be about 75 meters. According to a Mr. Callesen of Glacier Explorers, this event was either the third biggest, or second-equal biggest event in the known history of Tasman Lake.

6. CONCLUSIONSMarlborough

As indicated by the present review of the 21 February 2011 earthquake and of the previous and subsequent events,New Zealand is a region of considerable tectonic complexity. As stated, the country lies on the boundary between two large crustal plates, the Pacific Plate (moving approximately north-east) and the Indian Plate (moving roughly north). New Zealand is located at a transform boundary, where these two plates move laterally past one another, thus resulting in numerous earthquakes. The transform zone runs through both North and South Islands, although towards the North Marlborough the nature of the boundary changes and becomes a subduction zone, characterized also by volcanic activity. Because of New Zealand's proximity to the Alpine fault and the continuous, interactive and large tectonic movements along this great seismic boundary, more earthquakes and local tsunamis can be expected.

The present study helps document the tectonic stresses and seismicity of the Marlborough fault system along the northern part of South Island, and briefly evaluates the potential of future tsunami generation from earthquakes that may be generated near New Zealand's Hikurangi Trough, that may also impact the coasts of South Island as well as the coastlines near the City of Wellington on North Island.

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