

Final report to the Earthquake Commission on Project 13/U654

Southern Cook Strait Earthquake Response

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September 11 2014

Layman's Abstract

We deployed 21 seismometers along a 400-km line on the North and South Island, on either side of the Seddon Earthquake sequence, with the aim to image the Earth parallel to the subduction interface beneath the Lower North Island. The deployment lasted from 6 September 2013 to 21 January 2014. It consisted of two broadband seismometers borrowed from Massey University, 14 short period (2 Hz natural period) seismometers borrowed from the United States Passcal instrument center, and five seismometers borrowed from Y. Iio at Kyoto University. The line runs parallel to the subduction zone, with the expectation of learning how the structures change as the subduction zone shallows to the south. The data has been archived and is available for other researchers worldwide. Our initial images are interpreted as imaging the subduction interface as deepening from 25 km under Wellington to 35 km under southern Marlborough. These results are helping to build 3-D information about the plate interface. We hope that this will help us to understand future hazards posed by subduction thrust earthquakes in this region, and the feeding system for deep slow-slip earthquakes.

Contents:

Layman's Abstract (2)

Technical Abstract (4)

Fulfilment of Objectives (4)

Publications resulting from this project (5)

**Report from Hamish Hirschberg on his Summer Research
Scholarship (6)**

2014 AGU abstract (12)

Results and discussion behind 2014 abstract (13)

References (16)

Technical Abstract

We have recorded data from 21 seismometers that we deployed along the North and South Island, on either side of the Seddon Earthquake sequence, with the aim to image the Earth parallel to the strike of the subduction interface beneath the Lower North Island. The deployment lasted from 6 September 2013 to 21 January 2014. It consisted of two broadband seismometers borrowed from Massey University, 14 short period (2 Hz natural period) seismometers borrowed from the United States Passcal instrument center, and five seismometers borrowed from Y. Iio at Kyoto University. The data has been compiled and archived at VUW and at the United States IRIS data center.

Using the data, we perform seismic migrations using aftershocks of two $M > 6$ earthquakes as sources. The Southern Cook Strait earthquake sequence, beginning on 19 July 2013, included the 21 July $M=6.5$ and 16 August $M=6.6$ 2013 earthquakes, which were the largest shallow earthquakes to strike the Wellington region since 1942. This line of seismometers ties into the SAHKE line, which was an array of up to 900 seismometers that recorded air gun and explosion shots in deployments from 2009-2011. The SAHKE project characterized the structures perpendicular to the strike of the subduction zone. Our results use the SAHKE line as a starting point and look for strike-parallel variations in the depth of the Moho and other structures. Previous studies have suggested potential changes along strike in this region, and deep slow slip events (> 35 km) are also observed north of Wellington, further indicating that variation in properties exists along slab strike.

We have used 246 $M > 3$ earthquakes that occurred from September 2013 through January 2014 to create common receiver gathers. Multicomponent prestack depth migration of these receiver gathers, with operator antialiasing control and prestack coherency filtering, produces reflectivity sections using a 1-D velocity model derived from the SAHKE project. Relocation of aftershocks of the Seddon earthquakes using the deployment of a temporary array by New Zealand GeoNet facilitates the migration. An initial P-P migration shows a north-dipping reflector at 15-25 km depth under the earthquake sequence, and suggests the Moho at 20-25 km depth. From Wellington, a reflector dips very gently south from 25-35 km depth, which is probably the slab interface. These results are helping to build 3-D information about the plate interface. We hope that this will help us to understand future hazards posed by subduction thrust earthquakes in this region, and the feeding system for deep slow-slip earthquakes.

Fulfilment of Objectives

The main objective was to record aftershocks; we recorded 246 earthquakes over magnitude 3.0, which we have started using for imaging. We extended the interval between seismometers so that we could record the Moho depth down to the edge of the plate interface, so that instead of a 200-km line at 5 km spacing we have a 400-km line at 10 km spacing. The data has been sent to the IRIS data center in the US for archiving and we are also in contact with GeoNet about archiving a copy in New Zealand.

The deployment was carried out by students and staff of Victoria University. John Louie helped in the analysis of the data. Summer Scholar Hamish Hirschberg helped in station visits and in downloading and preparing the data for archival and in data analysis. Below is his report from his summer research. In addition to his report, he prepared a poster that was displayed in the VUW Summer Scholars Poster competition. He also helped us to prepare and discuss a poster about the project at the NZ Geosciences meeting in Christchurch in November 2013 and another to be given at the American Geophysical Union in December in San Francisco in December of 2014. We will also present the results at the NZ Geoscience conference in New Plymouth in November.

Because the summer research report provides the best introduction to the data collection, we include that first and then discuss the updated results that are behind the AGU abstract. All references are given at the end.

Publications (Abstracts) related to this project:

Savage M, Jacobs K, Heckels R, Shelley A, Dimech J, Walsh E, Martin S, Hirschberg H, Benson A, Warren-Smith E, Stern T, Townend J, Mcintosh J, Louie J, Henrys S, Bannister S, Frey B, Okaya D, Iio Y, Seddon earthquake aftershock structural investigation, In Reid, CM and Wandres, A. (eds). Abstracts, Geosciences 2013 Conference, Christchurch, New Zealand. Geoscience Society of New Zealand Miscellaneous Publication 136A., p. 84, 2013.

Jacobs KM, Hirschberg H, Louie JN, Savage MK, Bannister SC, Using aftershocks to Image the Subducting Pacific Plate in a Region of Deep Slow Slip, Hikurangi Margin, New Zealand, submitted to The American Geophysical Union Fall meeting, 2014, Eos Trans. AGU, 95(53), Fall Meet. Suppl., 2014.

Report by Hamish Hirschberg on his summer research project:

Seddon Earthquake Aftershock Investigation

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Abstract

The Seddon Earthquake Aftershock Investigation (SEASI) aimed to use the South Cook Strait and Eketahuna earthquake sequences to image the Earth parallel to the subduction interface beneath the Lower North Island. 21 seismometers were used in a deployment that lasted from 6 September 2013 to 21 January 2014, placed roughly parallel to the subduction interface in the Marlborough and Wellington regions. Data were collected for 246 magnitude 3 and greater earthquakes that occurred during this time. Common receiver gathers were created for each station before being migrated using a 1-D velocity model derived from a previous study. Initial migrations using P-P reflections indicate that it will be possible to create an image of subducting Hikurangi slab using the data gathered during SEASI. Work to image the slab and determine lateral variations along the interface is on-going.

Introduction

The Southern Cook Strait earthquake sequence, beginning on 19 July 2013, included the 21 July M=6.5 and 16 August M=6.6 2013 earthquakes, which were the largest shallow earthquakes to strike the Wellington region since 1942. These earthquakes were followed by the 20 January 2014 M=6.2 Eketahuna earthquake 180 km northeast, which resulted in a separate sequence of aftershocks. The accompanying aftershock sequences provided a series of natural seismic sources that could be used to investigate the structure of the interface between the Pacific and Australian Plates using refracted and reflected arrivals. These earthquakes occurred near the southern end of the Tonga-Kermadec-Hikurangi subduction zone, which reaches the surface at the Hikurangi Trough, offshore from the North Island's east coast. Here, the 120 Ma, thick oceanic crust of the Hikurangi plateau of the Pacific Plate is subducting beneath the Australian Plate at ~20 mm/yr (Wallace *et al.*, 2009). Beneath the Tararua Ranges, the Australian plate is underplated and the dip of the interface increases from 5° to the east to >math>15^\circ</math> to the west (Henry *et al.*, 2013). For the Seddon Earthquake Aftershock Investigation (SEASI), seismometers were deployed along the strike of the subduction interface to record the numerous aftershocks from the Southern Cook Strait sequence, as well as the earthquakes expected to occur to the north (which happened to include the Eketahuna sequence) and to the south of the array, allowing imaging parallel to the interface. A similar experiment conducted by Bourguignon *et al.* (2007) using the 2003 Fjordland earthquake was able to find crustal thickening and Moho anisotropy along the Southern Alps. This study uses earthquakes with similar locations as a repeating energy source in a similar manner to the way an explosion or set of explosions might be used in an active source study. The SEASI line was perpendicular to, and crossed, the transect of the SAHKE controlled source experiment, which involved up to 900 seismometers and provided a detailed image of the across strike structure of the subduction zone from both controlled sources and earthquakes (Henry *et al.*, 2013). The SAHKE experiment observed the presence of underplating beneath the Wellington region (Figure 1). SEASI aimed to complement the across strike image of the SAHKE line by determining the lateral continuity of the structure, including underplating. The SEASI data will also contribute to aftershock source studies and studies of slow-slip along the Kapiti Coast.

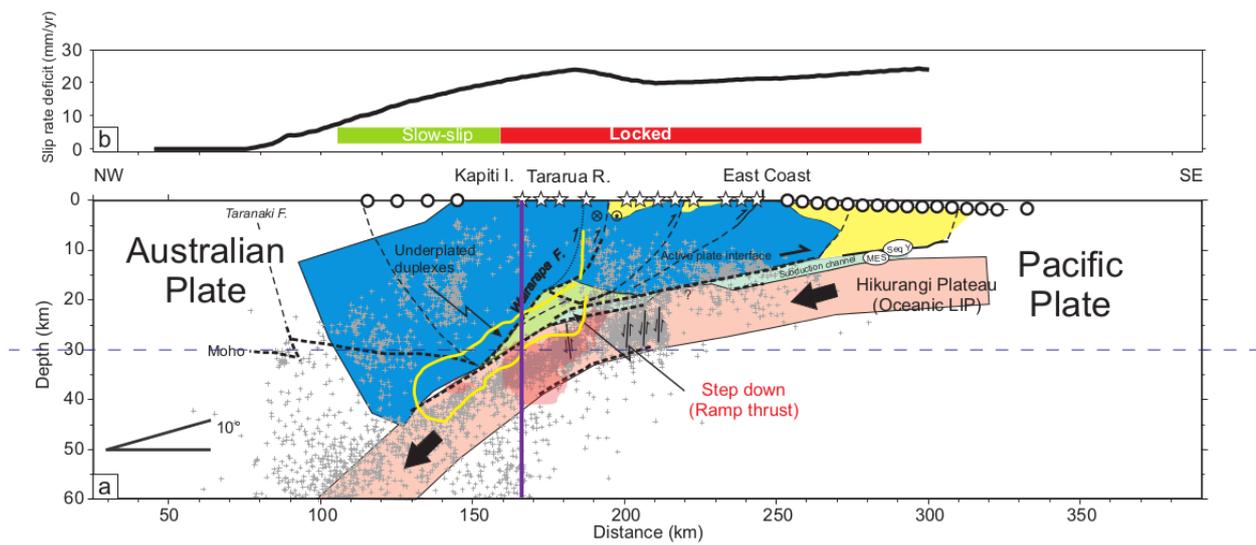


Figure 1: From Henrys et al. (2013), the structure along the SAHKE transect determined from controlled source experiments. The SEASI line intersected this cross-section around the purple line.

Method

Seismometer Deployment

A line of 21 seismometers was deployed along the Kapiti Coast, from Levin to Wellington, in the North Island and along the Awatere Valley in the South Island, roughly parallel to the strike of the subduction interface. The SEASI array, including permanent and temporary seismometers from GeoNet and the University of Kyoto, stretched 250 km with a spacing of 10 km, as shown in Figure 2(a). The SEASI array contained a variety of different seismometers: 14 2 Hz Mark Products L-22D seismometers from the PASSCAL Instrument Center in the United States; five 4 Hz Kinkei Systems KVS-300 from the University of Kyoto; and two intermediate period seismometers from Massey University. The GeoNet stations are short period and strong motion seismometers deployed and maintained by GNS Science. The SEASI temporary seismometer locations were chosen for their location parallel to the strike of the subduction interface where the bedrock in most cases greywacke, was close to the surface and has not been overlaid by large amounts of sediment. The hard greywacke does not attenuate seismic waves as much as soft sediments do, resulting in stations situated close to bedrock receiving more energy than stations situated on sediments. In the North Island, this resulted in a line following the edge of the hills. The stations were put in between 1 August and 6 September 2013 and pulled out between 21 January and 12 February 2014, resulting in a four month deployment. Each station was checked at least once during deployment to ensure that it was recording correctly, using a stomp test, and to download the data generated up to that time.

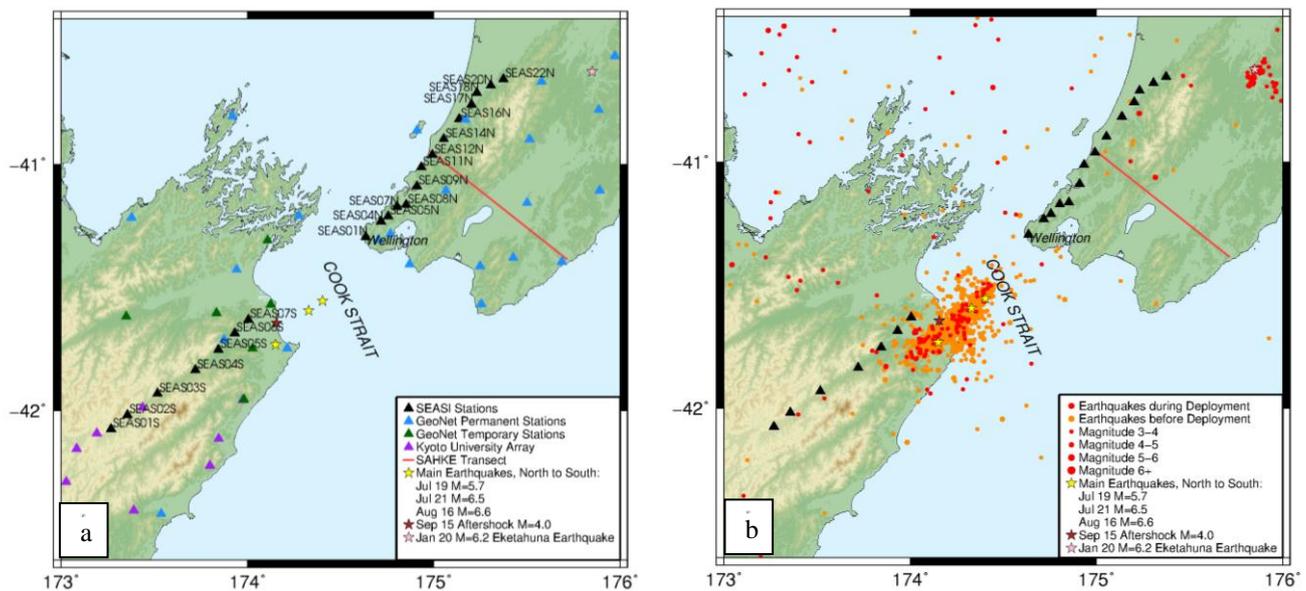


Figure 2: The Cook Strait region showing the location of the SEASI stations (black triangles) and the main earthquakes (stars). (a) Stations out during the SEASI deployment. GeoNet permanent and temporary stations (blue and green triangles, respectively), the University of Kyoto array (purple triangles), the SAHKE transect (brown line), and the main earthquakes (stars). (b) Location of earthquakes magnitude three and greater, as located by GeoNet, since 19 July until deployment of the array by 6 September (orange) and during deployment until 22 January (red). Circles are scaled by magnitude.

Data Processing

The data collected were converted from the format of the recorder to Seismic Analysis Code (SAC) (Goldstein and Snoko, 2005) format and cut from the origin time each earthquake to five minutes after the origin time. The earthquakes used were the 264 events of magnitude 3 or greater recorded by GeoNet from 6 September 2013 to 22 January 2014 in the region from 40° S to 43° S and from 171° E to 176° E (Figure 2(b)). The data from the 14 PASSCAL seismometers were also converted to miniseed format so that they could be submitted to the IRIS Data Management Center (DMC). Data were downloaded for the GeoNet permanent sites using GeoNet's Continuous Waveform Buffer (CWB) client for the same 246 events. *P* and *S* wave expected arrival times calculated by the TauP toolkit using the AK135 1D Earth model and used as guides for the manually picking that was then performed in SAC. Figure 3 shows the record section for the September 15 M=4.0 recorded at a selection of stations (earthquake location shown as brown star in Figure 2).

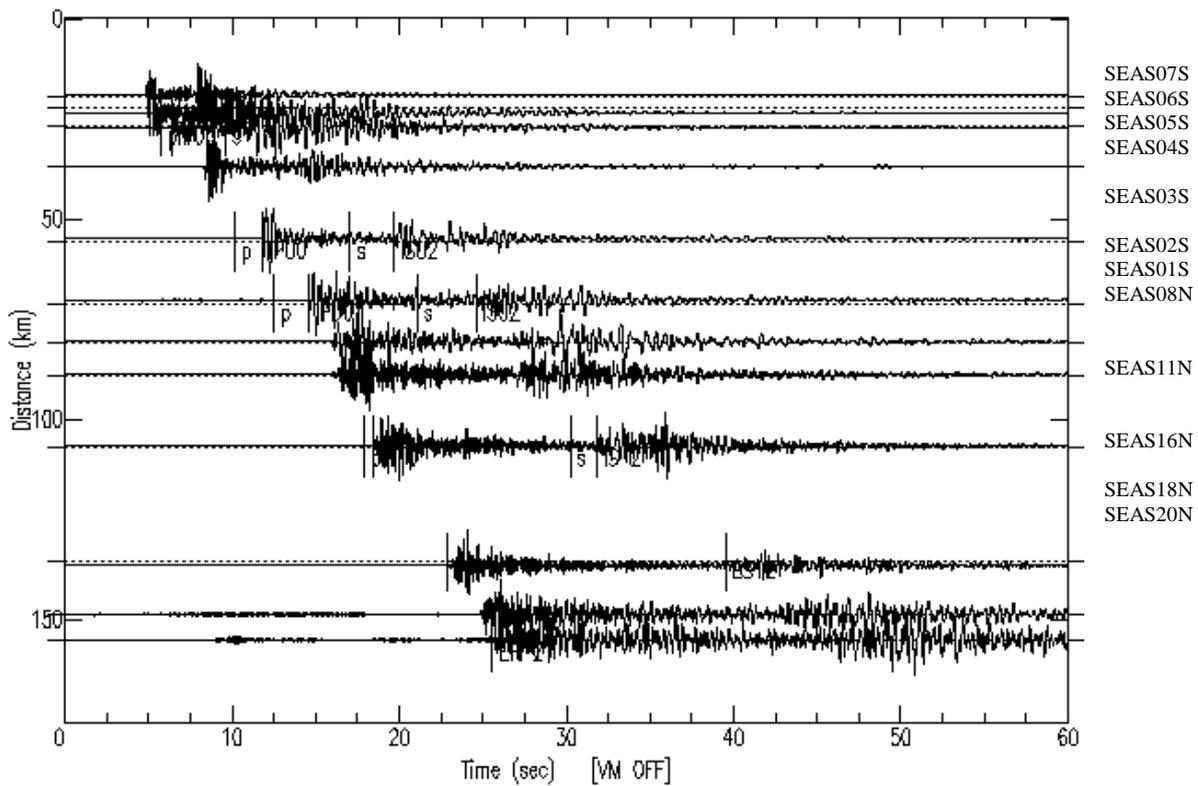


Figure 3: Vertical component record section for the 15 September $M=4.0$ aftershock, with picks, as recorded at selected stations and plotted using SAC. p and s denote the predicted arrival times and P and S waves, respectively, calculated by the TauP toolkit while the other picks were performed manually. Station names are to the right of the trace.

Reflection Analysis

The SAC files for each station were concatenated, from where they were loaded into the JRG viewing tool developed by John Louie, creating a common receiver gather (the set of data from multiple sources recorded by a single receiver). The data for each earthquake recorded at each station were centred and trace-equalised to remove the effects of earthquake magnitude and source-receiver distance variations. Centring is removal of the mean of the trace by subtracting the mean from the value at each point in time. Trace-equalisation is the multiplication of each point in a trace by a scalar to give the traces comparable amplitudes. A one dimensional velocity model shown in Table 1 provided by Stuart Henrys, based on the SAHKE experiment, was used to construct travel time tables. These tables were for points from the surface to 50 km depth and up to 450 km horizontally from the source, at a spacing of 0.5 km and were constructed for 101 source depths, again from the surface down to 50 km depth at a spacing of 0.5 km.

Table 1: Velocity model used to construct travel time plots

Depth (m)	P -wave Velocity (ms^{-1})
1,000	4,399.4
5,000	5,547.8
15,000	6,044.9
25,000	6,062.2
35,000	6,789.6
45,000	8,313.8
50,000	8,417.8

KIRCHHOFF-SUM ALGORITHM

$$R(\mathbf{X}, \mathbf{Z}) \leftarrow \sum_{\substack{\mathbf{S} \ \mathbf{g} \\ \mathbf{X} \ \mathbf{Z}}} \text{Data} [t(\mathbf{S}, \mathbf{g}, \mathbf{X}, \mathbf{Z})]$$

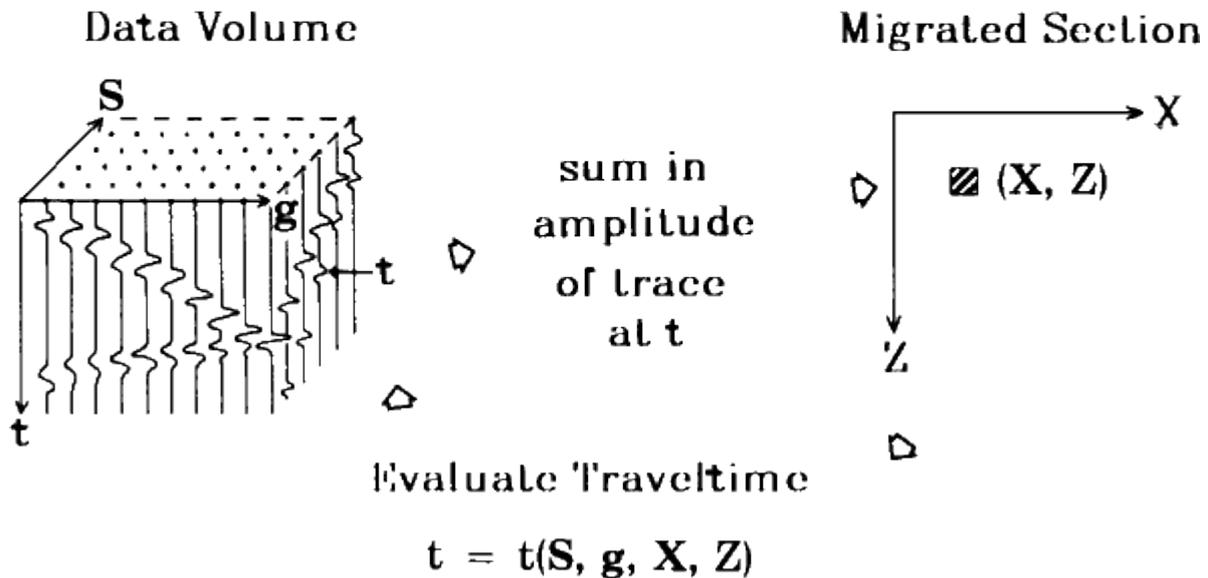


Figure 4: From Louie et al. (1988), schematic representation of the algorithm used to form the migrated image. For each source-receiver pair (S,g), the travel time to and from a given point (X,Z) in the depth section is calculated. The amplitude of the trace at that time is then summed into the point (X,Z) of the depth section.

The common receiver gathers using the vertical components from each station were migrated using these travel time tables and the methods of Louie *et al.* (2002) described below, focusing on the P-P reflections off the slab. In order to perform the migration, for each source-receiver pair, the travel time from the source to a given point in the section and then from that given point to the receiver is calculated using the travel time plots. The amplitude of the trace of that source-receiver pair is then added to the amplitude of that given point in the migrated section. This process, which is summarised in Figure 4, will result in all on the surface of an ellipsoid with the source and receiver at the two foci receiving the same amplitude for a given earthquake. It is, therefore, reliant on having enough source-receiver pairs for the amplitudes at points on the ellipsoids that are not reflectors to destructively interfere, while the true reflectors constructively interfere. The migrations excluded any energy that had less than 2 s travel time to help focus on reflected arrivals and were performed with an anti-aliasing spacing of 3.5 km. Anti-aliasing aims to remove any artefacts that may arise due to poor receiver spacing that renders two frequencies indistinguishable. They also used a squared obliquity factor, which suppressed steeply dipping reflectors in favour of shallower dipping reflectors because the plate interface was expected to be shallow dipping. Initial migrations for the whole line were created through the sum of individual station migrations to identify energy reflection points common to multiple stations and, as much as possible, cancel out artefacts. Further dip filtering was performed according to the methods of Hale and Claerbout (1983), using a low-pass Butterworth dip filter with a cut-off dip of 2 (corresponding to a dip of 63°) at 0.25 cycles per sample.

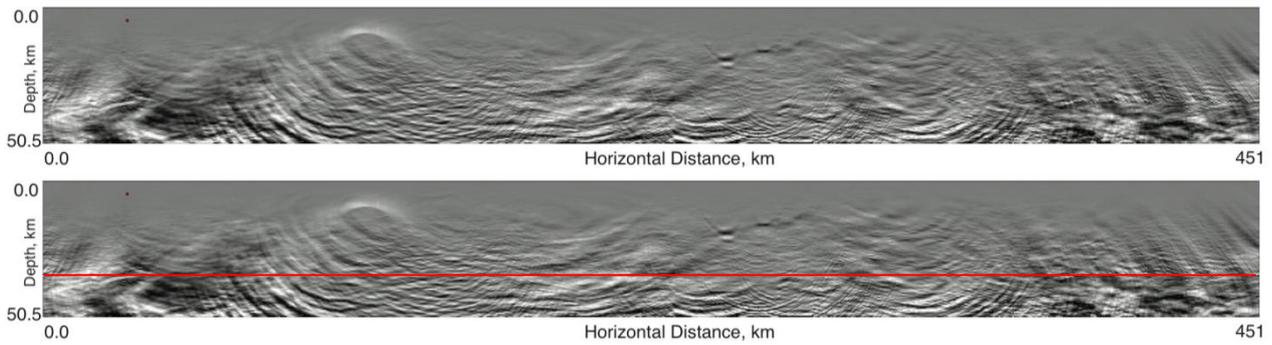


Figure 5: Initial image along the SEASI line using data filtered between 2 and 4 Hz from selected stations and earthquakes. Left to right runs 451 km from southwest to northeast, starting in Hamner Springs, and depth increases downwards to 50 km. The red line indicates the interpreted boundary at ~30 km depth.

Results & Discussion

Initial migrations, such as the one shown in Figure 5, using P-P reflections indicate that it will be possible to create an image of the subducting Hikurangi Plateau using the data gathered during SEASI. The interface appears to be at ~30 km depth, which is consistent with the results of Henrys *et al.* (2013). These migrations do, however, possess many artefacts that complicate the interpretation of any migration. The initial migrations currently contain traces from earthquakes that were not well recorded at that particular station. These noisy traces may be contributing to the presence of artefacts in the migration images and their removal may produce a clearer image. Filtering of the data may help identify and isolate the P-P reflections and, consequently, reduce the presence of artefacts in the final image. Initial migrations relied on a small portion of the data; the inclusion of more earthquakes and stations may help to clarify the desired structure by suppressing noise and reinforcing the true slab interface.

The initial migrations only used P-P reflections, where an incident *P* wave is reflected back as another *P* wave. Further migrations could be performed P-S (*P* wave reflected as *S* wave), S-P (*S* wave reflected as *P* wave), and S-S (*S* wave reflected as *S* wave) reflections, with the P-S and S-S reflections utilising the data from the horizontal components of each station. It is possible that different features of the slab will be more effectively imaged by different types of reflections, allowing an overall structure of the slab to be determined through a comparison of the individual reflection images.

Conclusion

SEASI successfully recorded data from the Southern Cook Strait earthquake and Eketahuna aftershock sequences on a line of seismometers along the Awarere Valley in Marlborough and from Wellington to Levin in the Lower North Island. Initial migrations of the data indicate that it will be possible to use the data gathered during SEASI to create an image of the subducting Hikurangi slab. Further processing of the data is, however, required before a clear image can be created, which may be supplemented by currently unused data. The work to image the slab and determine lateral variations along that interface is on-going.

Abstract submitted to AGU 2014

Using aftershocks to Image the Subducting Pacific Plate in a Region of Deep Slow Slip, Hikurangi Margin, New Zealand

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We present seismic migrations using aftershocks of two $M > 6$ earthquakes as sources. The Southern Cook Strait earthquake sequence, beginning on 19 July 2013, included the 21 July $M=6.5$ and 16 August $M=6.6$ 2013 earthquakes, which were the largest shallow earthquakes to strike the Wellington region since 1942. Following the two largest earthquakes we began the Seddon Earthquake Aftershock Structural Investigation (SEASI) and deployed a line of 21 seismometers stretching approximately 400 km along the strike of the Hikurangi subduction zone in order to use aftershocks to illuminate the structure of the subducted Pacific slab. The SEASI line ties into the SAHKE line, which was an array of up to 900 seismometers that recorded air gun and explosion shots in deployments from 2009-2011. The SAHKE project characterized the structures perpendicular to the strike of the subduction zone. Our results use the SAHKE line as a starting point and look for strike-parallel variations in the depth of the Moho and other structures. Previous studies have suggested potential changes along strike in this region, and deep slow slip events (> 35 km) are also observed north of Wellington, further indicating that variation in properties exists along slab strike.

We have used 246 $M > 3$ earthquakes that occurred from September 2013 through January 2014 to create common receiver gathers. Multicomponent prestack depth migration of these receiver gathers, with operator antialiasing control and prestack coherency filtering, produces reflectivity sections using a 1-D velocity model derived from the SAHKE project. Relocation of aftershocks of the Seddon earthquakes using the deployment of a temporary array by New Zealand GeoNet facilitates the migration. An initial P-P migration shows a north-dipping reflector at 15-25 km depth under the earthquake sequence, and suggests the Moho at 20-25 km depth. From Wellington, a reflector dips very gently south from 25-35 km depth, which is probably the slab interface. These results are helping to build 3-D information about the plate interface. We hope that this will help us to understand future hazards posed by subduction thrust earthquakes in this region, and the feeding system for deep slow-slip earthquakes.

Results and discussion behind the AGU abstract

Stephen Bannister and others at GNS have been working to relocate some of the aftershocks in the Southern Cook Strait sequence with data from the GeoNet permanent and temporary deployments. They have used the HypoDD relative earthquake location algorithm (Waldhauser and Ellsworth 2000) and phase-two automatic P arrival time picks along with the New Zealand 3D velocity model now used by GeoNet for routine locations. They have concentrated on a short period from September 6 – 17th and have relocated 388 earthquakes during that time. Seventeen of those are $M > 3.0$ events recorded by our array (Figure 6). Relocated earthquakes are expected to have location errors about ten times smaller than the original catalogue locations (Waldhauser and Ellsworth, 2000), and so these are expected to be on the order of 100 m, while catalogue locations generally have location errors of up to 1 km. The locations of these 17 events changed significantly. The location is of the utmost importance to migrations as we rely on that information to predict travel times and energy from individual events is less likely to constructively interfere to show the true reflectors if the locations are incorrect and do not vary systematically.

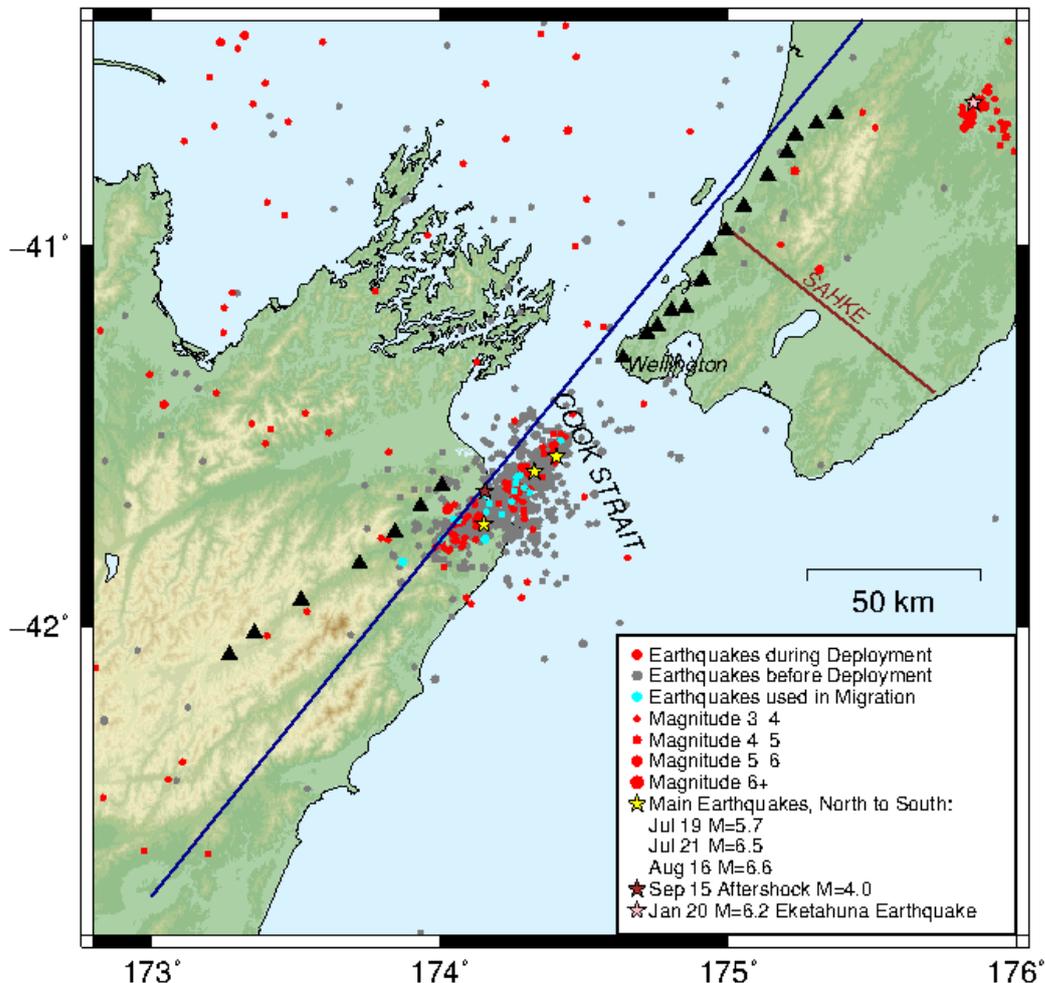


Figure 6. Earthquakes as in Figure 4 but here red circles are earthquakes recorded during the deployment and grey before the deployment. The blue circles are the earthquakes used in the migrations in Figures 7 and 8.

The migrations were repeated using only the 17 relocated earthquakes. The increased accuracy of the locations has allowed the coherent energy from different earthquakes to stack better, particularly directly under the earthquakes (Figure 7). A strong reflector with an apparent dip of about 30 degrees to the North appears directly under Seddon. When filters are applied to enhance near-horizontal structures, the nearly flat feature seen in Figure 5 as the stack of all GeoNet-located events is confirmed (Figure 8). We interpret the bottom of the wedge highlighted in Figure 8 as the top of the subducting slab since it is at the same depth as that imaged in the SAHKE deployment (Henrys et al., 2013) and in a tomographic study of the Marlborough region (Eberhart-Phillips and Reyners, 1998).

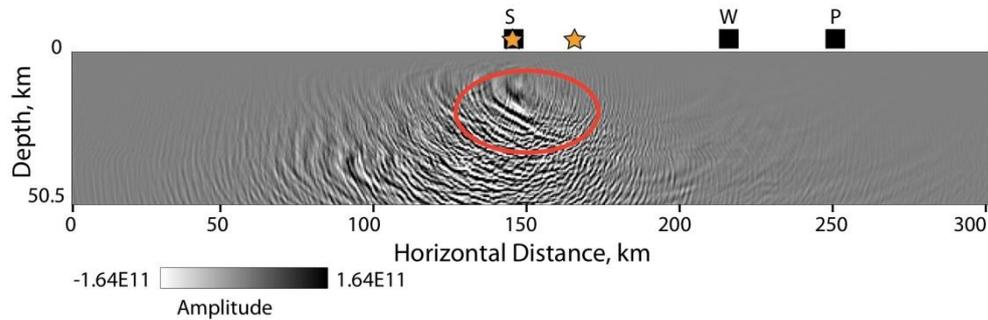


Figure 7. A 2-4 Hz bandpass filter and light operator anti-aliasing have been applied, which highlights a north-dipping reflector with an apparent dip of 30 degrees, directly beneath the main earthquake sequence at 15-25 km depth (inside the red circles). Black boxes along the top show the positions of the cities of Seddon (S), Wellington (W) and Paekakariki (P) as distances from the endpoint of the migrated section (-42.7, 173.0)

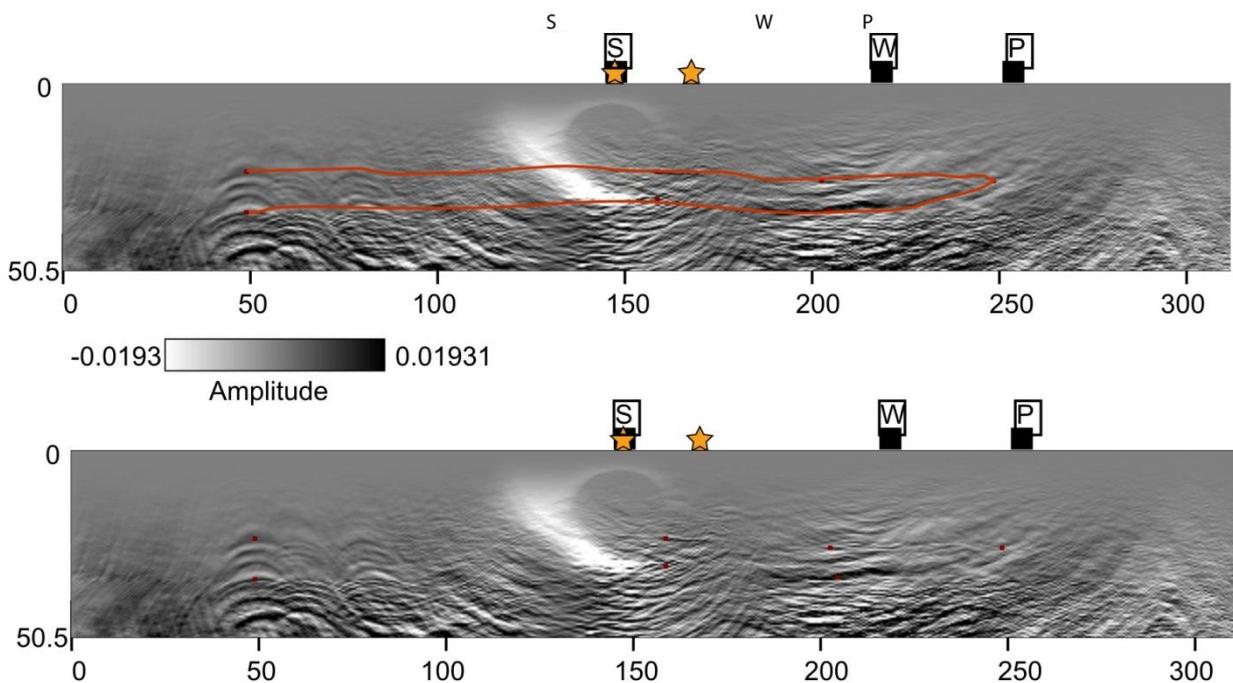


Figure 8. Migration along the entire line using the 17 relocated earthquakes. A dip-filter (favoring horizontal structures), and full operating anti-aliasing have been applied, but unlike fig. 7, the individual traces have not been filtered. The upper diagram shows an interpretation, in which a red line highlights the potential location of a wedge pinching out to the north under Paekakariki. Black boxes along the top show the positions of Seddon (S), Wellington (W), and Paekakariki (P) as distances from the endpoint of the migrated section (-42.7, 173.0).

Relocating the other earthquakes used in the stack in Figure 5 is expected to better define the subducting interface, removing some of the “wavy structure” because more receiver source pairs will emphasize real reflectors. We plan to run relocations ourselves now with the remaining earthquakes in our catalogue. The 17 events used in the migration above will be given the strongest weighting so that the remaining events are relocated relative to those best locations.

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