**SEISMOTECTONICS OF A LOCKED
SUBDUCTION PATCH: THE SOUTHERN
HIKURANGI MARGIN**

By

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"Reason is a choice. Wishes and whims are not facts, nor are they a means to discovering them. Reason is our only way of grasping reality - it's our basic tool of survival. We are free to evade the effort of thinking, to reject reason, but we are not free to avoid the penalty of the abyss we refuse to see.

-Terry Goodkind, *Faith of the Fallen*

Abstract

Subduction zones produce the largest earthquakes on the planet, where rupture along the plate interface can result in the release of stress over large areas, with up to tens of meters of slip extending from below the surface to the trench. The regional stress field is a primary control on the faulting process, ergo understanding the regional stress field leads to a better understanding of the current and future faulting in the area.

Abundant new seismic and continuous Global Positioning System (cGPS) data in the southern North and northern South Island, New Zealand, make it possible to characterize stress and strain parameters throughout the southern Hikurangi subduction zone. Stress orientations calculated within the subducting plate, the overriding Australian plate, and due to gravitational forces reveal that stress throughout the subducting system varies across the southern North Island. Margin parallel motion is being accommodated by shear deformation west of the Wairarapa fault, whereas margin perpendicular motion is being accommodated east of the Wairarapa fault.

Stress parameters within the double Benioff zone (DBZ) were characterized in terms of two bands of seismicity. In the deep region of the DBZ, inversion the upper band of seismicity shows down-dip tension, while the lower band shows compression. Tension in the upper band and compression in the lower band is consistent with bending stresses. In the shallow region of the DBZ, the inversion of both the upper and lower bands seismicity showed tension; this is indicative of slab pull.

Shear-wave splitting of stacked waveforms of local earthquakes recorded on 291 three-component stations showed an average fast azimuth of N-S to NNE-SSW, west of the Wairarapa fault. A fast azimuth orientation of N-S to NNE-SSW is sub-parallel to the local major faults. This indicates that the observed anisotropy west of the Wairarapa fault is structurally derived. East of the Wairarapa fault, within the Wairarapa Basin, the average fast azimuth orientation is NNW-SSE. Because the fast azimuth orientation showed no dependence on station-earthquake distance, depth, or back azimuth and is perpendicular to major local faults; it has been interpreted as being reflective of the SHmax orientation.

cGPS daily solutions for long-term and inter-slow slip events (inter-SSE) time periods show distinctly differing regions of shear strain rate in the southern North Island and northern South Island. Compression and positive (clockwise) rotation in the southern North and northern South Island was observed using both datasets. Inter-SSE time periods resulted in lower magnitude strain parameters than those calculated dur-

ing time periods including SSEs. These datasets shows that strain parameters change on time scales of SSEs (< 10 years).

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Chapter 1

Introduction

1.1 Context and Reasoning

Earthquakes represent a clear and present danger to life and infrastructure throughout New Zealand. Thorough seismic hazard evaluation is contingent on an understanding of the past and present seismological dynamics of a region. The goal of this study is to add to the current understanding of stress and strain throughout the southern Hikurangi locked subduction patch, in order to provide background stress and strain information for future seismic hazard analysis of North Island, New Zealand. Characterization of stress and strain provides invaluable information when evaluating current and future deformation and seismic hazards in a region.

The analysis of stress and strain in this study will serve as background information in the evaluation of future seismic hazards in the southern North Island, specifically in the characterization of onshore deformation in the southern North Island and the seismotectonic dynamics of the southern Hikurangi subduction locked patch.

The most up-to-date seismic hazard model for New Zealand (Stirling et al., 2012, Figure 1.1) incorporates fault and seismicity distribution, including paleoseismological data, into a probabilistic seismic hazard analysis method developed by Cornell (1968). The most recent seismic hazard model includes 13 subduction interface sources, which incorporates observations of interface coupling (Wallace et al., 2009), in an effort to better account for seismic hazards associated with the Hikurangi subduction system. An expert panel (comprised of the co-authors of (Stirling et al., 2012)) was needed to develop a weighting system, based on subduction margin characteristics (e.g., seismicity, plate interface coupling, and slow-slip earthquakes, etc.), in order to quantify the 13 subduction interface source models. Though the 2012 seismic hazard model is reasonably up-to-date, future iterations can be improved upon by the addition of more seismic and tectonic characterization, which this thesis seeks to provide.

A large portion of the data used in this study was provided by a collaborative ef-

Figure 1.1: 2012 New Zealand Seismic Hazard Model from Stirling et al. (2012). Seismic hazard maps for 475 and 2500 year return periods for shallow soil site conditions (10% and 2% probability of exceedance in 50 years, respectively). (a) peak ground acceleration (PGA) for 475 year return. (b) spectral acceleration (SA) 0.5 s 475 year return. (c) SA 1.0 s 475 year return. (d) PGA for 2500 year return. (e) SA 0.5 s 2500 year return. (f) SA 1.0 s 2500 year return. (g) 2002 Seismic Hazard model PGA 475 return. Continued

Figure 1.1: continued. Largest hazards are along the Alpine fault trace, and in the northern South and southern North Islands.

fort among GNS Science, Victoria University of Wellington, and Earthquake Research Institute (University of Tokyo, Japan), in conjunction with Ministry of Economic Development and Crown Minerals. The data were part of the Seismic Array Hikurangi Experiment (SAHKE I and II), a controlled-source and passive seismic imaging experiment. The goal of the SAHKE projects were to investigate the physical parameters controlling locking on the plate interface and the characterization of slip processes beneath the southern North Island of New Zealand (GNS Science Report 2010/48 and 2011/50).

1.2 Thesis Format

Chapter 2 outlines the theoretical background of the methods utilized in the proceeding chapters. Location of microseismicity is calculated with several location algorithms and velocity models. The location algorithms used are Hypocenter (Lienert et al., 1986; Lienert and Havskov, 1995) and NonLinLoc (Lomax et al., 2000; Lomax, 2011), with additional relocation done with HypoDD (Waldhauser and Ellsworth, 2000). Within the various location algorithms a one dimensional velocity model from Henrys et al. (2013) and a three dimensional velocity model from Eberhart-Phillips et al. (2010) was used. Focal mechanisms and stress inversions were calculated using Bayesian methods from Walsh et al. (2009); Arnold and Townend (2007), respectively. Shear-wave splitting analysis is preformed in Chapter 5 using the Multiple Filter Automatic Splitting Technique (MFAST) from Savage et al. (2010). Strain parameters calculated in Chapter 6 are done using algorithms from Lamb and Smith (2013); Lamb (2015). Algorithm particulars are expanded upon in proceeding chapters.

The objective of Chapter 3 is to compare and contrast stress orientations within the subducting Pacific plate and the overriding Australian plate, in order to discern if stresses within the subducting plate are being transferred to the overriding plate at southern North Island, New Zealand. This is achieved by the inversion of focal mechanisms for stress orientations in the subducting Pacific plate, the calculation of the shear-wave fast azimuth (an approximation of SHmax) within the overriding Australian plate, and the determination of SHmax due to gravity based on crustal structure and topography of the Australian plate. Chapter 3 was published as: Stress Orientations in a Locked Subduction Zone at the Southern Hikurangi Margin, New Zealand in the *Journal of Geophysical Research: Solid Earth*, with myself (Dominic Evanzia) as lead author and Thomas Wilson, Martha Savage, Simon Lamb, and Hamish Hirschberg as co-authors. I was responsible for writing and submission of the manuscript, phase picking, the earthquake relocations, focal mechanism calculations, and stress inversions. I am also responsible for incorporating the stress inversions data, shear-wave splitting measurements from Wilson (2016), and gravitational stress data provided by Hamish Hirschberg. Guidance on the methods, interpretations, and editing was provided by Martha Savage and Simon Lamb. Supplemental materials are in Appendix

A.

The objective of Chapter 4 is to characterize stress parameters within the Double Benioff Zone beneath the southern North Island, in an effort to better understand stress within and deformation of the subducting Pacific plate. This is accomplished by first clustering relocated focal mechanisms into the upper and lower bands of seismicity, and then by inverting those clusters for stress parameters (i.e., maximum, intermediate, minimum stress, and SHmax orientation). Chapter 4 is in the process of being submitted as: *Illumination of Deformation by Bending Stresses within the Southern Hikurangi Double Benioff Zone in the New Zealand Journal of Geology and Geophysics*, with myself (Dominic Evanzia) as lead author and Simon Lamb, Martha Savage, and Tim Stern, as co-authors. I am responsible for writing of the manuscript, phase picking, earthquake relocations, focal mechanism calculations, and stress inversions. Guidance with concepts, interpretations, and editing was provided by Tim Stern, Martha Savage, and Simon Lamb. Supplemental materials are in Appendix B.

The objective of Chapter 5 is to determine near surface seismic anisotropy and stress parameters (e.g., fast azimuth/SHmax and delay time) using earthquakes recorded on a high-density array, during the active source (Seismic Hikurangi Array Experiment) SHAKE II experiment. The density of the array allows for the unique opportunity to stack waveforms in order to attempt to increase signal to noise ratio. Seismic anisotropy is measured on hand-picked phases from 21 local earthquakes, using the Multiple Filter Automatic Splitting Technique (Savage et al., 2010). Chapter 5 is in the process of being submitted as: *Stress-Controlled Anisotropy Revealed by a High-Density Seismic Array Across Southern North Island, New Zealand in the Journal of Earth and Planetary Science Letters*, with myself (Dominic Evanzia) as lead author and Martha Savage, Stuart Henrys, and David Okaya, as co-authors. I was responsible for writing of the manuscript, phase picking, and implementation of shear-wave analysis. Guidance with methods, interpretation, and editing was provided by Martha Savage, Stuart Henrys, and David Okaya. Supplemental materials are in Appendix C.

The objective of Chapter 6 is to calculate strain rate parameters, using continuous Global Position system (cGPS) data, to examine how stress relief via slow-slip events (SSEs) and large earthquakes, affect strain in the southern North and northern South Islands of New Zealand. This is achieved by using three cGPS datasets: (1) long-term cGPS velocity, which includes slow-slip events (SSEs); (2) inter-SSE cGPS velocity; (3) co-seismic cGPS velocity during the 2016 Kaikoura earthquake. Additionally in Chapter 6, preliminary dislocation modeling methods from Okada (1985, 1992) and Lamb and Smith (2013) are used to examine the degree to which SSEs affect the slip dynamics on the plate interface below the southern North Island. Supplemental materials are in Appendix D.

1.3 Tectonic Overview

The New Zealand portion of the Pacific-Australian plate boundary consists of oblique subduction, back-arc rifting, transform motion, and continental collision (Beavan and Haines, 2001) (Figure 1.2). Relative to the Australian plate, the Pacific plate is converging ~ 50 mm/yr west in northern New Zealand, ~ 40 mm/yr south-west in central New Zealand, and ~ 30 mm/yr south-south west in southern New Zealand (DeMets et al., 1990, 1994). The tectonics of the North Island are dominated by subduction at the Hikurangi Margin, back-arc rifting in the Taupo Volcanic Zone (TVZ), and strike-slip faulting in the North Island Seismic Belt (NISB) (Beanland and Haines, 1998; Wallace et al., 2004). In the South Island, the dominating tectonic process is continental collision and strike-slip faulting along the Alpine Fault (Walcott, 1984, 1998) (Figure 1.2).

Slip on the Hikurangi subduction plate interface is not uniform (Walcott, 1984). Wallace et al. (2004, 2009, 2012) show there to be a slip deficit of $\sim 20 - 30$ mm/yr on the slab interface below the southern North Island, indicating that the subducting Pacific and overriding Australian plates are partially 'locked' or 'coupled'. A locked or coupled subduction interface would have several impacts on the dynamics of the subduction zone. A locked subduction interface would imply the presence of increased amounts of stress on the interface. The accumulation of this stress could manifest in some combination of two end-members: (1) a mega-thrust subduction earthquake located in proximity to the locked portion of the subduction interface or (2) the allocation and transmission of stress to the overriding plate, leading to more numerous large earthquakes on crustal faults.

The transition from oblique subduction at the southern Hikurangi margin to oblique continental collision on the northernmost extent of the Alpine fault occurs at the northernmost South Island (Figure 1.2). Relative plate motion transitions from slip along the subduction mega-thrust to upper plate faults zones. The Marlborough fault zone dominates the northern South Island, it contains a number of strike-slip faults that are oblique to the underlying subducting slab (Langridge et al., 2005, 2016). Amount of displacement in the Marlborough fault zone decreases from northwest to the southeast, with the greatest amount occurring along the Wairau fault (the northernmost continuation of the Alpine fault), then the Awatere fault, with the Hope fault having the least of these three (Eberhart-Phillips et al., 2014).

The major surface structural features of the southern North Island are NE-SW striking faults (Litchfield et al., 2014) (Figure 1.2). The relative motion of the Pacific and Australian plates is associated with the occurrence of numerous magnitude ≥ 3 earthquakes (>33000 in the last 10 years quakesearch.geo.org.nz). Since 1834 there have been 28 large ($M \geq 7$) earthquakes and one great earthquake, the M_{8+} 1855 Wairarapa earthquake in New Zealand (Stirling et al., 1998). The most recent large earthquake was the 2016 $M_W 7.8$ Kaikoura earthquake, which occurred in the northeastern South

Figure 1.2: Overview of New Zealand tectonics. The New Zealand portion of the Australian and Pacific plate boundary is marked by the Hikurangi Margin (Blue), in the North Island, and the Alpine Fault (Blue) in the South Island (Coffin et al., 1998). Other major features of the North Island are the Taupo Volcanic Zone (TVZ), the extent of which is marked by the dashed-magenta lines and the Slow-Slip earthquakes (Green) (Wallace and Beavan, 2010), which originate on the plate interface of the subduction zone, and active faults (Red) throughout the North and South Island (<https://data.gns.cri.nz/af/>)

Island.

For further characterization of study area specific tectonics, see individual chapters.

Chapter 2

Theoretical Background

2.1 Earthquake Location

2.1.1 Linearized Location

The simplest earthquake location calculation is performed when considering an earthquake as a point source within a homogeneous half-space model (i.e., a single layer of material buttressed against a vacuum). The hypocenter position (H) can be defined, in a Cartesian coordinate system:

$$H = (X, Y, Z) \quad (2.1)$$

The calculated arrival time at station i (T_i^c) of a given seismic phase from a hypocenter is given by the following:

$$T_i^c = \frac{\sqrt{(X - X_i)^2 + (Y - Y_i)^2 + (Z - Z_i)^2}}{V} + T_0 \quad (2.2)$$

where (X_i, Y_i, Z_i) is the i^{th} station's position, V is the velocity of the homogeneous half-space, and T_0 is the origin time of the earthquake (Stein and Wyssession, 2009).

Equation 2.2 is non-linear and has four unknowns (X, Y, Z , and T_0). The reliability of a hypocenter and origin time can be measured by a misfit factor, the residual (R_i), at each station. Uncertainties in locations are directly related to imprecise phase arrival picks and uncertainties in the velocity model used. R_i is the difference between the observed (T_i^o) and calculated travel times (T_i^c).

$$R_i = T_i^o - T_i^c \quad (2.3)$$

With increasing station coverage and knowledge of the velocity characteristics of the subsurface, the average travel-time residual from each station-earthquake pair would become more minimized, resulting in a more reliable hypocenter location.

Geiger (1910) developed an iterative inversion method for locating local (within or near to the array of stations) earthquakes. *Geiger's* method solves for the location by linearizing the location equation in a least-squares manner, utilizing the Taylor series of the hypocenter coordinates. This method describes the residual (R_i) by the following:

$$R_i = \frac{\partial T_i}{\partial X} \Delta X + \frac{\partial T_i}{\partial Y} \Delta Y + \frac{\partial T_i}{\partial Z} \Delta Z + \Delta T_0 \quad (2.4)$$

where Δ describes variations made to hypocenter parameters (e.g. X, Y, Z , origin time) in order to minimize the residual. The partial derivatives above can be calculated (in a half-space) from Equation 2.2 describing arrival time (T_i) in a homogeneous half-space:

$$\frac{\partial T_i}{\partial X} = \frac{X - X_i}{V} \times \frac{1}{\sqrt{(X - X_i)^2 + (Y - Y_i)^2 + (Z - Z_i)^2}} \quad (2.5)$$

$$\frac{\partial T_i}{\partial Y} = \frac{Y - Y_i}{V} \times \frac{1}{\sqrt{(X - X_i)^2 + (Y - Y_i)^2 + (Z - Z_i)^2}} \quad (2.6)$$

$$\frac{\partial T_i}{\partial Z} = \frac{Z - Z_i}{V} \times \frac{1}{\sqrt{(X - X_i)^2 + (Y - Y_i)^2 + (Z - Z_i)^2}} \quad (2.7)$$

$$\frac{\partial T_i}{\partial T_0} = 1 \quad (2.8)$$

2.1.2 Non-Linear Location

In this study earthquake relocations were initially solved as a linearized problem using HYPOCENTER (Lienert et al., 1986; Lienert and Havskov, 1995) within the SEISAN package (Havskov and Ottemoller, 1999). Final locations were determined using NonLinLoc, a probability based non-linear location package (Lomax et al., 2000). Using NonLinLoc to obtain final earthquake locations is advantageous because of the program's ability to incorporate a 3D velocity model and because hypocenter solutions are described by a posterior probability density function (PDF), which incorporates uncertainties. Furthermore, the PDFs are used in later programs (focal mechanism and stress inversion), which allows for explicit use of location uncertainties to determine the uncertainties throughout the stress analysis process.

NonLinLoc implements the probabilistic formulation of inversion developed by Tarantola and Valette (1982) and Tarantola (1987). The probabilistic formulation uses normalized and non-normalized PDFs to characterize desired parameters:

$$P(X \leq x \leq X + \Delta X) = \int_X^{X+\Delta X} f(x) dx \quad (2.9)$$

where the probability (P) of a parameter (x) being between $X \leq x \leq X + \Delta X$ is described by a normalized density function $f(x)$.

The goal is to constrain an unknown parameter (p) (e.g., hypocenter location) given the observed data (d) (e.g., station locations, travel time, initial hypocenter location). While integrating over the data (d) space, a probabilistic solution can be characterized by a PDF ($\sigma_p(p)$) if the density function of the model parameters $\rho_p(p)$ and observation $\rho_d(d)$ are each independent and there is a theoretical relationship $\theta(d, p)$ between the data and model parameters:

$$\sigma_p(p) = \rho_p(p) \int \frac{\rho_d(d)\theta(d|p)}{\mu_d(d)} \delta(d) \quad (2.10)$$

where $\theta(d|p)\mu_p(p)$ is the conditional density function of the data given the model parameter (p) and $\delta(d)$ represents the differential of the variable d . The functions $\mu_p(p)$ and $\mu_d(d)$ are null information probability density functions, where no prior knowledge exists. Tarantola and Valette (1982) showed that if you assume the observed arrival times and theoretical relationship have Gaussian uncertainties and the prior information on origin times is uniform, then it is possible to integrate over the observed data (Equation 2.10) to calculate a maximum likelihood estimation of the origin time and PDF for hypocenter coordinates.

This study utilizes the Oct-Tree grid search method (Lomax, 2011), within Non-LinLoc. The Oct-Tree method employs an iterative grid search, where a course grid (defined by 8 corner nodes) is subdivided into eight cells (64 nodes). The cell with the highest location probability is then split into eight more cells. Cell division is repeated until a predetermined threshold of node-to-node length (0.001 km), maximum number of nodes (100000), or number of possible locations (1000) is achieved.

2.1.3 Double-Difference Location

Additional relocations of earthquakes were performed using HypoDD (Waldhauser and Ellsworth, 2000; Krischer, 2015), a double-difference location method, which simultaneously relocates sets of earthquakes. It combines P- and S-wave differential travel times derived from cross-spectral methods with travel-time differences from catalog data. It minimizes residual differences for pairs of earthquakes by adjusting the vector differences between hypocenters.

Equation 2.10 gives the travel-time residual (r_k^i) for a single earthquake(i)-station(k) pair, where $r_k^i = (t_k^{obs} - t_k^{cal})^i$, t_k^{obs} and t_k^{cal} are the observed and theoretical travel time, and $\Delta m^i = (\Delta x^i, \Delta y^i, \Delta z^i, \Delta t^i)$ is the difference in hypocenter location and origin time for a given perturbation of parameters:

$$\frac{\partial t_k^i}{\partial m} \Delta m^i = r_k^i \quad (2.11)$$

where $\frac{\partial}{\partial m}$ represents the partial derivative with respect to the parameter m . Cross-correlation at a single station is used to measure the travel-time difference between

two earthquakes at that station. The residual (dr_k^{ij}) from cross-correlation travel-time difference between two earthquakes (i, j) was described by Frechet (1985) as:

$$\frac{\partial t_k^{ij}}{\partial m} \Delta m^{ij} = dr_k^{ij} \quad (2.12)$$

where $\frac{\partial}{\partial m}$ represents the partial derivative with respect to the parameter m , $\Delta m^{ij} = (\Delta x^{ij}, \Delta y^{ij}, \Delta z^{ij}, \Delta t^{ij})$ is the change of relative hypocenter locations, t_k^{ij} equals the time difference between each earthquake (i and j), and $dr_k^{ij} = (t_k^i - t_k^j)^{obs} - (t_k^i - t_k^j)^{cal}$, where dr_k^{ij} is the double-difference travel-time residual (the difference between the observed and calculated values of the difference in time between two earthquakes at the same station) (Waldhauser and Ellsworth, 2000).

The Waldhauser and Ellsworth (2000) double-difference location method assumes a constant slowness vector for earthquakes close together. The location method relies on a reasonably dense catalog with closely-spaced earthquakes.

2.2 Focal Mechanisms and Stress Inversion

2.2.1 Focal Mechanisms

A focal mechanism is a characterization of slip on a plain (a fault) at an earthquake hypocenter. Focal mechanisms provide a visual representation of the propagation of an earthquakes's seismic energy, displayed a projection of the southern hemisphere of a sphere 'a beach ball'. A focal mechanism displays regions of dilatation (tension and compression) that result from initial ground movement at the hypocenter. A negative dilation response is indicated by a 'down' seismic signal response, while an 'up' response is expressive of a positive dilation response. A focal mechanism (θ) is described by two nodal planes, the strike (ξ), dip (δ), and rake (λ) angles (Figure 2.2).

$$\theta = (\xi, \delta, \lambda) \quad (2.13)$$

Nodal planes define the boundaries between regions of "tension" and "compression". There are two nodal planes, one describes the geometry of the fault plane, the other is known as the auxiliary plane and is orthogonal to the fault plane. Movement on either nodal plane would be satisfactory to generate the displayed focal mechanism. The fault plane is chosen in concert with other geologic factors (e.g., known stress field orientations, fault orientatons, rock fabric orientations, aftershock patterns, etc.).

The strike (ξ) of a fault describes the angle of clockwise rotation (right-hand rule: fault dips to the right), from true north, of the intersection of the fault plane to a horizontal surface. The angle of rotation is measured from $0^\circ \geq \xi \geq 360^\circ$ (Figure 2.1).

The dip (δ) is a measurement of the angle downwards to the fault plane from a horizontal plane. The dip is measured from the right of the strike orientation and is

Figure 2.1: Example of the how a strike (ξ), dip (δ), and rake (λ) is measured on a fault. The red plane is the original location of blue plane pre faulting.

measured from $0^\circ \geq \delta \geq 90^\circ$ (Figure 2.1).

The rake (λ) angle is measured on the fault plane and is a characterization of the motion of the hanging wall, counter-clockwise from the strike direction. Rake is measured from $0^\circ - 360^\circ$ (Figure 2.1).

There are three end-member faulting styles: (1) normal; (2) reverse; (3) strike-slip. Focal mechanisms with styles reflective of more than one end member are classified as oblique (e.g., oblique-normal, oblique-reverse). The style of faulting is determined via rake (λ) angle.

- $210^\circ > \text{normal (red)} > 330^\circ$
- $30^\circ < \text{reverse (blue)} < 150^\circ$
- $330^\circ > \text{strike-slip sinistral (green)} < 30^\circ$
- $210^\circ > \text{strike-slip dextral (green)} > 150^\circ$

According to the Andersonian faulting theory (Stein and Wysession, 2009), each of the three faulting styles are representative of a particular arrangement of the applied stresses (assuming one principal stress is vertical). Focal mechanisms display quadrants of the P- (white Figure 2.2) and T- axis (colored Figure 2.2). The quadrant with the P-axis in it will contain maximum compressive stress (S_1) direction, while the quadrant with the T-axis in it will contain the the minimum compressive stress (S_3) direction. Normal faulting (Figure 2.2 red) occurs in an extensional environment, resulting in a vertical S_1 -axis and a horizontal S_2 - and S_3 -axis. Reverse faulting (Figure 2.2 blue) is initiated in a compressive environment resulting in a horizontal S_1 - and S_2 -

Figure 2.2: Example of normal, reverse, and strike-slip focal mechanisms. In map-view, focal mechanisms are displayed the lower hemisphere. Colored regions indicate first motion compression, white regions indicate first motion expansion. Arrows indicate relative motion across fault plane. On strike-slip focal mechanisms dots show slip towards, while pluses show slip away. In order to determine which nodal plane is the fault plane independent information is needed. Note, these are end member examples of focal mechanisms, oblique focal mechanisms are predominate in nature and would be a combination of either normal and strike-slip or reverse and strike-slip.

axis and a vertical S3-axis. Strike-slip faulting (Figure 2.2 green) results in horizontal S1- and S3-axes and a vertical S2-axis.

For the particulars on the focal mechanism package used see Chapter 3: *Stress Orientations Throughout the Southern Hikurangi Margin*.

2.2.2 Stress Inversion

An individual focal mechanism can only inform about which quadrants the stresses (maximum, intermediate, minimum compressive stress) acted on that particular medium, at that time. In order to characterize a regions entire stress field a study must incorporate a multitude of focal mechanisms located throughout the area of interest. The inversion of a cluster of focal mechanisms results in the calculation of that cluster's average stresses.

A synthetic 3×3 tensor is used to characterize stress acting on a given medium. Given the symmetry of the stress tensor, there are six independent variables describing the magnitude (in bold) and orientation of the maximum ($S1$), intermediate ($S2$), and minimum ($S3$) compressional stresses. The inversion of focal mechanisms can provide sufficient information to calculate the orientations of $S1$, $S2$, and $S3$, as well as the ratio of the relative magnitudes of the stresses. In this study, in order to easily compare with previous studies (e.g., Townend et al., 2012) in New Zealand, stress ratio (R) is defined

Figure 2.3: Shear-wave splitting example. As a polarized shear-wave (blue) enters an isotropic medium, the shear-wave is unsplit (blue), upon entering an anisotropic medium, the shear-wave becomes split (magenta & green). Delay time describes the time difference between the arrival of the split waves. Fast azimuth is the orientation of the faster of the two split waves (magenta).

as:

$$R = \frac{\mathbf{S1} - \mathbf{S2}}{\mathbf{S1} - \mathbf{S3}} \quad (2.14)$$

where the bold characters indicate the stress magnitude. For particulars on the stress inversion estimation package used see Chapter 3: *Stress Orientations Throughout the Southern Hikurangi Margin*.

2.3 Seismic Anisotropy

Seismic anisotropy is a property of a medium that describes the phase velocity dependence on propagation direction or particle motion. Splitting of the shear-wave occurs when a polarized shear-wave encounters an anisotropic body, causing the polarized wave to split. One of split waves will propagate parallel along the fast azimuth (often cracks or crystalline fabric), whereas the other will propagate orthogonal to the fast azimuth or the azimuth of original polarized wave depending on the nature of the anisotropic medium (Figure 2.3).

Shear-wave splitting measurement parameters of interest in this thesis are: (1) fast azimuth of the two polarized waves and (2) delay time between the fast and slow polarized waves. The splitting parameters were calculated using the Multiple Filter Automatic shear-wave Splitting Technique (MFAST) (Savage et al., 2010). For the particulars of the MFAST splitting package see Chapter 6: *Shear-wave Anisotropy Across the Southern North Island, New Zealand*.

2.4 Continuous Global Positioning System

Continuous Global Positioning System (cGPS) datam measure the change in position relative to a designated reference point. Publicly available cGPS daily-solution

data were downloaded from <http://www.geonet.org.nz>. The cGPS data are processed by GeoNet using the GAMIT and GLOBK software developed at Department of Earth Atmospheric and Planetary Sciences of the Massachusetts Institute of Technology (MIT). The following section summarizes the processing method (http://www.geonet.org.nz/data/supplementary/gnss_time_series_notes).

1. Solutions are calculated each day for data 1, 3, 30 and 90 days behind Coordinated Universal Time (UTC).
2. Orbits are held fixed and not solved for.
3. International GNSS Service (IGS) final orbits for data 30 and 90 days behind, rapid orbits for data 3 days behind, ultra-rapid orbits for data 1 day behind.
4. Earth orientation parameters from International Earth Rotation and Reference Systems Service (IERS) Bulletin A values (USNO and USND for most recent solutions).
5. Ambiguity resolution by wide-lane and narrow-lane L1 and L2 frequency (= LC, ionosphere free) combination.
6. Absolute IGS phase center corrections for satellite and receiver antennas from igs08-wwww.atx file, provided by MIT.
7. Ocean loading from FES2004 grid ocean tide model.
8. Atmospheric delay estimated using the "global mapping function" (GMF) (Böhm et al., 2006).
9. Atmospheric loading not applied.
10. Depending on the increasing size of the network in time, a loosely-constrained solution is done as increasing numbers of clusters, each of less than about 30 stations and 6 tie sites, that are then combined during the reference frame realization.
11. A final solution is aligned to International Terrestrial Reference Frame (ITRF) 2008, using a 6-parameter Helmert transformation (translation and rotation) onto available and good quality IGS sites in Australia, the south-west Pacific and the Antarctic.

2.4.1 GPS Reference Frame Transformation

The methods of Lamb and Smith (2013) were used to transform the cGPS station velocities from the International Terrestrial Reference Frame (ITRF2008) (Altamimi et al., 2012) to an Australian plate Reference Frame (AURF). In this method, the Australian

plate Euler pole is calculated in the ITRF2008 reference frame, then the inverse of that Euler pole is applied to the New Zealand cGPS station velocity data.

For information on calculation of station velocity, strain parameters, and dislocation modeling, see Chapter 6: *cGPS Strain Parameters in the Southern North and Northern South Island of New Zealand*.

Chapter 3

Stress Orientations Throughout the Southern Hikurangi Margin

3.1 Abstract

We analyze the orientation of the stress field in the southern Hikurangi subduction zone, New Zealand, using focal mechanism inversions, S wave splitting fast directions, and gravitational stresses. Here the oceanic Pacific plate is being obliquely subducted beneath the continental Australian plate in the New Zealand plate boundary zone. The study makes use of 399 earthquakes for focal mechanism inversion and 425 earthquakes for shear wave splitting analysis, located with a network of seismic stations spanning southern North Island. We distinguish between stresses in the Pacific plate (from focal mechanism inversion) and Australian plate (from S wave fast directions) and gravitational stresses, in three regions: Western, Central Basin, and Eastern. In the Western region, the principal axis of horizontal compression (SHmax) is oriented NE-SW, parallel to the margin, in the upper Australian and lower Pacific plate. In the Central Basin, SHmax in the Australian plate is oriented NW-SE, perpendicular to the margin; in the lower subducting Pacific plate SHmax is oriented NE-SW. In the Eastern region, SHmax is oriented NE-SW in the upper plate, while in the lower plate there is a change in orientation to NNW-SSE. We interpret the stress orientations of the lower plate in the Western and Central Basin regions as a consequence of bending of the subducting plate. Sources of upper Australian plate stresses are likely to be bending stresses, gravitational stresses, and tectonic loading, with differing relative magnitudes across the study area.

3.2 Introduction

Subduction zones are the sites of the largest earthquakes on the planet, where rupture of the plate interface results in the release of stress over large areas, with tens of meters of slip extending up to the surface in the trench. One of the primary controls

on the faulting process is the regional stress field (Kusznir et al., 1991; Zoback, 1992; Townend et al., 2012). New Zealand, where the oceanic Pacific plate is being obliquely subducted beneath the continental Australian plate. Southern North Island is one of the few places in the world that allows for an on-land seismic deployment above the shallow part of a subduction zone, making it possible to study the subduction zone in greater detail using onshore seismic and geodetic networks.

3.2.1 Tectonic Setting

In New Zealand's southern North Island, the contemporary Pacific-Australian plate boundary consists of oblique subduction along the southern Hikurangi margin at ~ 38 mm/yr (Figure 3.1) (Beavan and Haines, 2001; Beavan et al., 2002).

Surface structural features of the region are dominated by NE-SW striking reverse and dextral strike-slip faults (Figure 3.1, NZ active fault database, www.gns.cri.nz). Partitioning of deformation results in predominantly dextral shear on the northwestern margin of the onshore part of the plate boundary, with a greater component of reverse faulting farther to the SE toward the trench, a pattern that is also seen in geologic and geodetic measurements (Lamb and Vella, 1987). The combined motion on the major onshore faults accommodates 60-90% of the margin-parallel motion (Langridge et al., 2005), whereas margin-perpendicular motion is mainly taken up by the subduction thrust (Wallace et al., 2012). This predominantly occurs through episodic earthquake slip on time scales of hundreds to thousands of years. However, the region is also subject to prolific microseismicity, with thousands of earthquakes of $M > 3$ in the last 10 years (www.geonet.org.nz), as well as occasional large ($M \geq 7$) earthquakes and the M_{8+} 1855 Wairarapa event (Stirling et al., 1998). In addition, slow slip events on the megathrust, lasting weeks to months, occur offshore and farther west, at depths of ~ 30 to 60 km, roughly every 6 years (Wallace and Beavan, 2010; Lamb and Smith, 2013; Wallace et al., 2014).

The distribution of interseismic slip on the plate interface varies along the length of the Hikurangi subduction zone, with the greatest proportion of free slip in the northern part (Walcott, 1984; Wallace et al., 2004, 2009, 2012). However, high-resolution decadal campaign GPS measurements of velocity (Beavan et al., 2016) and decadal continuous GPS time series (www.geonet.org.nz) show that the southern part of the plate interface in the vicinity of southern North Island is locked, with strain and stress build up due to slip on the plate interface at depths > 22 km (Darby and Beavan, 2001; Wallace et al., 2004; Lamb and Smith, 2013). Darby and Beavan (2001) note that if the coupling at the plate interface is variable then maximum coupling occurs between 16 and 24 km depth. Furthermore, Lamb and Smith (2013) determine the locking point on the interface, which ranges in depth from 5 to 15 km in the northernmost part of the Hikurangi margin beneath the northeast North Island, to ~ 35 km in the southernmost section, south of the study area in the northeast South Island. The sudden release of

Figure 3.1: Southern Hikurangi subduction zone and seismic array map. Topography is in a gray scale. Red contours show subduction plate interface as modeled by Williams et al. (2013) and bold grey and black lines show traces of active faults; this is same for all relevant subsequent figures. Locations of seismic stations are shown by triangles: Seismic Array Hikurangi Experiment (cyan, November 2009 - March 2010), Wellington Regional Seismic Network (magenta, permanent), and New Zealand National Seismic Network (orange, permanent). Map inset: Study area (box) in context of overall New Zealand tectonics. Pacific plate (subducting) motion relative to Australian plate (overriding) shown by red arrow is 38 mm/yr. Blue lines are plate boundaries (e.g., location of Hikurangi Margin (HM), North Island Seismic Belt (NISB), and the Alpine Fault).

the accumulated stress could result in a large megathrust earthquake, which would have far-reaching effects throughout North Island and South Island of New Zealand (Power et al., 2008).

Allen (1978) and Lamb and Vella (1987) used ~ 100 years of retriangulation geodetic measurements to determine the pattern of horizontal strain rates between the Australian and Pacific plates in southern North Island, dividing the strain rates into two components: (1) a shortening rate normal to, and (2) a shear rate parallel to, the strike of the Wairarapa fault. East of the Wairarapa fault, the shortening rate is greater than the shear rate, meaning that compression is the principal deformation force in this region. However, west of the Wairarapa fault, the shear rate is greater than the shortening rate, demonstrating that in this region, deformation is primarily the result of dextral shear parallel to the strike of the Wairarapa fault (Lamb and Vella, 1987; Beanland and Haines, 1998).

3.2.2 Previous Studies

There have been few direct observations of the stress field in the southern Hikurangi margin. Lamb (2015) combined strain rates from neotectonic deformation with estimates of the variation in gravitational potential energy (in effect, stresses due to gravity) to infer total deviatoric stress magnitude for the New Zealand plate boundary zone, averaged over the whole thickness of the crust (top ~ 25 km) or lithosphere (~ 100 km). This showed that average deviatoric stresses are in the range 130 MPa, comparable to the gravitational stresses themselves.

Gledhill and Stuart (1996) used shear wave splitting from local earthquakes, recorded on the temporary Tararua array, to study crustal anisotropy in the southern North Island, New Zealand. They determined a fast direction in the Australian plate that was orientated $051^\circ \pm 18^\circ$ for earthquakes between 5 and 42 km depth. For earthquakes in the depth range 77-260 km, in the subducted Pacific plate beneath the Taranaki Basin, they determined a fast direction with an azimuth of $041^\circ \pm 15^\circ$. These orientations are subparallel to both the strike of the subduction zone and to dominant faults in the overlying Australian plate. Audoin et al. (2000) and Brisbane et al. (1999) concluded that this orientation for the deeper earthquakes reflected trench-parallel flow of the mantle. SKS phases indicated anisotropy in the mantle beneath the lower plate to be oriented $028^\circ (\pm 11^\circ)$ (Gledhill and Stuart, 1996). Variation in frequency content for different phases suggested some variations despite a general NE-SW fast alignment (Marson-Pidgeon and Savage, 1997, 2004; Karalliyadda, 2014).

Previous earthquake focal mechanism studies in the southern North Island have focused on the kinematics of active deformation, and their implications for slip partitioning, plate coupling, and earthquake hazards (Reyners et al., 1997; Reyners, 1998; Webb and Anderson, 1998; McGinty et al., 2000). Strong coupling between the Aus-

tralian and Pacific plates was inferred from slip vectors of intraplate thrust earthquakes (Webb and Anderson, 1998) and an absence of low-angle thrust events at the plate interface (Reyners et al., 1997). Reyners (1998) related the amount of plate coupling to the risk of a large subduction thrust earthquake in the southern North Island, inferring that the subduction zone here is capable of producing a M_W 8.0 earthquake. Townend et al. (2012) analyzed the orientation of the stress field throughout the New Zealand plate boundary zone using earthquake focal mechanisms, but with only sparse data in the southern North Island. This showed that in the northernmost South Island and the southwest North Island, at a depth of 20 km to 50 km, the maximum horizontal stress orientation (SHmax) is subparallel to the strike of the Hikurangi subduction trench. This is consistent with the finding of McGinty et al. (2000) for the northern South Island. Also in the northern South Island, Balfour et al. (2005) found that the average angle between SHmax and the strike of local major faults was $\sim 60^\circ$, indicating that the faults were poorly oriented for slipping and were thus weak.

In this study the stress field orientations in the lower plate are determined from stress inversions of focal mechanisms, while the stress field orientations of the upper plate are characterized by crustal anisotropy measurements. We compare these observations with both gravitational stress orientations averaged over the top 25 km of Australian plate and predicted bending stress orientations in the subducted Pacific plate. This approach may help improve our knowledge of the locked section of the Hikurangi subduction zone by distinguishing between the stress field in the overriding and subducting plates.

3.3 Seismic Data

We use earthquakes recorded at 50 stations (48 short period and 2 broadband) that form part of the Seismic Array Hikurangi Experiment (SAHKE) seismic array, deployed between November 2009 and March 2010 (Seward et al., 2010; Henrys et al., 2013). We supplement these stations with permanent GeoNet stations: 3 broadband and 16 short period seismic stations (Figure 3.1). The 2010 Seismic Array Hikurangi Experiment (SAHKE) was designed to investigate the physical parameters controlling a locked megathrust and to characterize slip processes on a segment of the Hikurangi system beneath the southern North Island, New Zealand, summarized in Seward et al. (2010) and Henrys et al. (2013). The experiment was a collaborative effort between GNS Science, Victoria University of Wellington, University of Tokyo, Japan (Earthquake Research Institute), and the Ministry of Economic Development, Crown Minerals.

During the ~ 5 month period of the SAHKE deployment, 425 earthquakes (M_{2+} to M_{5+}) detected at depths < 50 km were used for crustal anisotropy measurements, and 399 (M_{2+} to M_{5+}) earthquakes were used as an initial dataset for determining focal mechanisms (Figure 3.2).

Figure 3.2: Location of 425 earthquakes for S wave splitting (magenta) and 399 earthquakes, used as an initial data set for focal mechanism stress inversion (cyan) portions of this study. See Figure 3.1 for background description. Dashed line A to A' indicates strike of cross-section map. Cross section: Cross-sectional view of earthquake location from A to A'. Dashed line (black) is projected view of plate interface contours. Location differences between common earthquakes used in both data sets are due to the relocation of the focal mechanism data set.

3.4 Methodology

To facilitate comparisons between our inferred stress directions from focal mechanisms, seismic anisotropy and gravitational stresses, we consider stress orientations in the upper (Australian plate) and lower (subducted Pacific plate) plates for three regions spanning southern North Island (Figure 3.3): (1) west of the Wairarapa fault (Western region), (2) between the Wairarapa and Dry Creek faults (Central Basin region), and (3) east of the Dry Creek fault (Eastern region). The boundary between the Western and Central regions is the Wairarapa fault, and the Central Basin region is at a lower average topographic level than the other two (Figure 3.3). Within each region, average SHmax orientations derived from shear wave splitting and gravitational stresses were calculated with the MATLAB Circular Statistics Toolbox (Directional Statistics) package (Berens et al., 2009).

3.4.1 Shear Wave Splitting Measurements

Anisotropy in the crust is generally modeled in terms of the effect of near-vertical fluid filled microcracks throughout the crust (Crampin, 1981; Savage, 1999). Differential stresses in the crust will preferentially close cracks that are aligned perpendicular to the maximum principal stress direction (Nur, 1971). Shear wave speed is decreased for waves traversing the cracks, and so cracks in the vertical plane cause a seismic anisotropy with the maximum shear wave speed (fast direction) parallel to the open cracks. Therefore, the maximum horizontal compressive stress (SHmax) orientation is roughly parallel to the shear wave fast directions (e.g. Crampin, 1994). The time between the first shear wave arrival and its orthogonal component is called the delay time. Most shear waves arrive at the surface with near-vertical paths, so cracks in the horizontal plane are not well sampled by shear wave splitting studies.

Shear wave splitting measurements from local earthquakes tend to be scattered (Zhang et al., 2007; Johnson et al., 2011; Karalliyadda and Savage, 2013; Savage et al., 2016). Often shear wave splitting fast orientations change rapidly in short distances, and there is little dependence between delay time and depth. In these cases, anisotropy is interpreted to be shallow. For example, the direction of shear wave splitting near Wellington varied rapidly even between stations spaced only a few kilometers apart (Gledhill, 1991). This is expected because cracks generally close rapidly with depth (Nur and Simmons, 1969) due to the pressure of the overburden. However, mineral and structural alignment can also cause anisotropy (Do Nascimento et al., 2004), so the results need to be examined in concert with other methods.

Often measurements at a single station may be consistent for the same earthquake location but vary for different earthquake locations (Zhang et al., 2007; Johnson et al., 2011). Yet when splitting measurements are averaged regionally, the measurements should align with the maximum horizontal stress (Savage et al., 2016), although some-

Figure 3.3: Map of splitting fast Azimuths. The study area is divided into three regions, used in subsequent sections of study: Western, Central Basin, and Eastern. (a) Mean fast direction splitting results for earthquakes recorded on the SAHKE array only by depth, above (orange) and below (green) 30 km. Depth of earthquake does not have a great effect on fast direction results. (b) All (purple) and mean (yellow) fast direction measurements from earthquakes of all depths. Results show clear variation in splitting in the Western, Central Basin, and Eastern regions. Yellow bars with red outlines are specifically referred to in the text. (c) Rose diagrams displaying the orientations of the mean shear wave fast direction within the three regions (Western, Central Basin, and Eastern) of the study area. The rose diagram illustrates the spread of the orientations of the shear wave fast direction. Diagrams are scaled by maximum number of events per region.

times they are more consistent with regional structures or with faulting (Zinke and Zoback, 2000; Balfour et al., 2005).

Multiple processing steps were used to obtain S arrival times in the study area. Earthquakes located by GeoNet (www.geonet.org.nz) were used together with a 1-D velocity model (Henrys et al., 2013) and the TauP traveltimes routine (Crotwell et al., 1999) to calculate both the expected phase arrival times as well as the ray incidence angles. The expected phase arrival times were used as guides for both manual and automatic picks. Automatic P arrival times were made using Automatic Picking function (Allen, 1978), using Seismic Analysis Code (Goldstein et al., 2003; Goldstein and Snoke, 2005). These P arrival times were used to determine a search window for automatic S waves picks using SpickerC (Castellazzi et al., 2015), which is based on the Diehl et al. (2009) Spicker function. The SpickerC function combines three different phase picking methods: (1) STA/LTA, (2) Polarization filters, and (3) Autoregression modeling. A weighting scheme was applied to the results of the three picking processes to determine the final pick and obtain an error estimation on those picks (Diehl et al., 2009). No relocations were carried out for this part of the study, because measurements of delay time and fast direction are not strongly dependent on location.

For crustal anisotropy analysis, fast direction and delay time were calculated for individual earthquake-station pairs using the Multiple Filter Automatic Splitting Technique (MFAST) (Savage et al., 2010). MFAST uses the following steps: (1) a set of bandpass filters is applied to the S arrival waveform to find the filter that yields the maximum product of the signal-to-noise ratio (SNR) and bandwidth; (2) using multiple measurement windows, a grid search over the fast azimuth and the delay time parameter space is performed on the waveforms filtered at the best bandpass filter. The search determines the fast direction and delay time that best corrects for splitting, as measured by the minimum of the smallest eigenvalue of the corrected particle motion (Silver and Chan, 1991); (3) an unsupervised cluster analysis (calculation of cluster's R^2 value) (Teanby et al., 2004) is applied to the fast direction azimuth and delay times to determine the most stable solution; (4) MFAST automatically grades the earthquake-station pair measurements from A to D, based on the following four criteria: (I) SNR, (II) uncertainty, (III) distinctiveness of the cluster (cluster with smallest R^2 value), and (IV) whether the measurement is null. Null measurements occur when either there is little anisotropy or when a wave arrives at an anisotropic medium with its polarization parallel or perpendicular to the fast direction in these cases, the wave is not split. Null measurements can be identified by U-shaped confidence intervals, which allow for any amount of splitting in two narrow bands of possible fast directions that are parallel to the calculated incoming polarization direction. The MFAST program considers null measurements to be measurements with delay times within 80% of the highest value allowed in the grid search (1.0 s here, local event delay times should be $<<1$ sec), or with fast directions within 20° of either in the incoming polarization or its

perpendicular.

In this study we use the A and B quality measurements with incidence angles less than 35° from the vertical, calculated using the earthquake locations and the 1-D velocity model of Henrys et al. (2013). A and B quality measurements meet the following criteria: (I) $\text{SNR} > 3$, (II) error in fast direction < 25 degrees, and (III) the measurement is not null.

As shown by Wilson (2016) in his Figure 3.5, scatter plots of the delay times versus raypath lengths show that the delay time is not cumulative along the path length of the ray. This suggests that the delay time does not result from a homogeneous region of anisotropy but is likely to be due to near-surface stress or structures. To further examine the anisotropy as a function of depth, we divide the earthquake measurements, recorded on the SAHKE array only, into two depth bins: (1) above (226 events) and (2) below 30 km (209 events) (Figure 3.3a). There was an attempt to further subdivide the data into a third depth bin of above 15 km, but there were only 22 earthquakes, an insufficient amount to calculate reliable results. Plots of delay time versus the dominant frequency of the incoming waveforms for splitting measurements indicate that there is no dependency of delay time on the frequency of the incoming waves (i.e., splitting is frequency independent).

3.4.2 Focal Mechanism Inversion

Earthquake focal mechanisms can serve as in-situ gauges of stress because earthquakes occur when the ambient stress field exceeds the local strength of rocks or the frictional strength of a preexisting fault, and the kinematics of rupture of a random array of faults directly reflects the orientation of the stress field. Arnold and Townend (2007) developed a Bayesian method to invert clusters of earthquake focal mechanisms for the orientation of the stress field. They assumed that the stress field is homogeneous and faults are randomly oriented, with equal probability of either nodal plane being the fault plane, and that individual faults are blind to rupture on neighboring ones. Subject to these assumptions, and with sufficient unique earthquake clusters, it should be possible to determine the variation of the orientation of the stress field, within a given region.

Starting with initial locations by GeoNet (www.geonet.org.nz), 399 earthquakes arrivals and polarities were repicked by hand using the Seisan Earthquake Analysis Software (SEISAN) package (Havskov and Ottemoller, 1999). The handpicks were then used for hypocentral calculations, initially with a 1-D seismic velocity model (Henrys et al., 2013) and HYPOCENTER (Lienert et al., 1986; Lienert and Havskov, 1995), and then refined with a full 3-D velocity model (Eberhart-Phillips et al., 2010) and the non-linear location package NonLinLoc (Lomax et al., 2000).

The stress inversions and focal mechanisms, using P wave polarities, were calcu-

lated using the Bayesian method of Arnold and Townend (2007) and Walsh et al. (2009), respectively. The Walsh et al. (2009) method of calculating focal mechanisms models the entire data generation process and incorporates multiple observational errors (i.e., hypocenter location, seismic velocity structure, and P wave polarities). The Arnold and Townend (2007) stress inversion method incorporates fault plane ambiguity and observation errors. As in Walsh et al. (2009), focal mechanisms (θ) are expressed as a function of their strike (ξ), dip (δ), and rake (λ):

$$\theta = (\xi, \delta, \lambda) \quad (3.1)$$

Computed focal mechanism were deemed reliable based on two quality control parameters: number of polarity picks ($P\rho$) and precision (τ). Arnold and Townend (2007) expressed by the following relationship:

$$\sigma_\theta = e^{3.9155 - 0.5659 \log \tau} \quad (3.2)$$

where σ_θ is the standard deviation of the uncertainties in the angles of ξ , δ , and λ , of a given θ . The minimum number of $P\rho$ needed and the minimum value of τ for a focal mechanism to be considered reliable in this study were 5 and 2, respectively, where a precision of 2 is equivalent to approximately a 33° standard deviation of the strike, dip, and rake directions. Although a minimum of 5 polarity picks for a focal mechanism is unusually low, the Walsh et al. (2009) Bayesian method allows for location of the polarity pick on a focal sphere to be taken into account, when assessing focal mechanism quality (i.e., error estimation). Thus, a focal mechanism with a low number of P wave polarity picks could return a low-error focal mechanism, given stations in ideal locations on the focal sphere.

Focal mechanisms, located only in the subducting plate with at least 5 polarity picks and an error less than 33° are used in the stress inversions. We separated the earthquakes into clusters based on a visual analysis of which region they were located (i.e., Western, Central Basin, and Eastern) (Figure 3.4a).

The stress inversion routine returns the orientation of the three principal stresses and the stress ratio for each cluster of earthquakes (Arnold and Townend, 2007). The orientation of SHmax is calculated with the method of Lund and Townend (2007), making it possible to compare with SHmax derived from shear wave splitting and gravitational stresses. Stress ratio is defined here as $(S1 - S2)/(S1 - S3)$, where $S1$ = maximum compressive stress magnitude, $S2$ = intermediate compressive stress magnitude, and $S3$ = minimum compressive stress magnitude (e.g. Townend et al., 2012).

Figure 3.4: Map of Bayesian calculated focal mechanisms and clusters of focal mechanisms used to calculate stress parameters. Red contours and grey faults are as in Figure 3.1. (a) Three clusters used for stress inversion: Western (light blue), Central Basin (purple), and eastern (yellow). Grey earthquakes were not used in stress inversion. (b) Focal mechanisms calculated using a Bayesian method from Walsh et al. (2009). Focal mechanism are colored by rake: $150^\circ < \text{Normal} < 30^\circ$; $30^\circ > \text{Reverse} < 150^\circ$; $30^\circ > \text{Strike slip} > 150^\circ$; $150^\circ > \text{Strike slip} > 150^\circ$. Dashed A to A' line indicates strike of cross-section map. Cross section: Cross-sectional map of focal mechanism projected onto a vertical plane from A to A'. Dashed line (black) location is projected view of plate interface contours. The subducting plate (potentially including plate interface earthquakes) has $\sim 58\%$ normal focal mechanisms. (c) Three stress inversions calculated in each one of the three regions. Stereonets show the distribution of S1 (red), S2 (green), and S3 (blue) axes, as well as the orientation of SHmax (black dashed lines). The posterior probability mean (solid circle) and mode (open circle) are colored as per stress axis.

3.4.3 Gravitational Stresses

Unlike stress measurements from earthquake data, which only contain information about the directions and relative magnitudes of the principal stresses (Arnold and Townend, 2007), it is straightforward to calculate the magnitude and orientations of gravitationally induced stresses, given the density of crustal rocks, together with crustal structure and surface topography (i.e., stress = density $\times$ gravity $\times$ thickness). Here we concentrate on the stress orientations to compare with the other stress measurements.

We use the topography in the southern part of the Hikurangi margin to calculate the SHmax directions and magnitudes of the gravitationally induced stress field, averaged over the top ~ 25 km (the maximum depth of the plate interface in this area) of the crust (Lamb, 2015), with an average density of 2.67 g/cm^3 , using the method of Flesch et al. (2001). The Flesch et al. (2001) method involves solving the stress balance equations for an isotropic viscous medium, subject to a mean vertical stress determined by topography, and a horizontal boundary condition of zero deviatoric stress. Using the Flesch et al. (2001) method, vertically averaged deviatoric stresses due to variations in gravitational potential energy were solved using a thin sheet approximation. The modeling was performed using finite difference methods in MATLAB. The stress field reflects long-term variations in gravitational forces at a length scale of tens of kilometers and thus is representative of these stresses at comparable depths—note that short wavelength shallow stresses at depths < 5 km may be quite different from those we calculate, reflecting the elastic response to short wavelength topography (Molnar, 2004). Based on the wavelength of the topography in the southern North Island, there is approximately a $\pm 10^\circ$ error associated with the SHmax orientations. The gravitational stress field provides a calibration of the magnitude of the total stress field in the Australian plate, and if it dominates the total stress field, then we would expect to see SHmax varying closely with topography, aligned more-or-less parallel (at high points) or orthogonal to (at low points) topographic gradients.

3.5 Results

3.5.1 Shear Wave Splitting

After incidence angle filtering, 13,807 A and B quality S wave splitting measurements were made from 425 earthquakes. Table 1 presents the number of measurements, circular mean, and 95% confidence interval calculated for individual stations. Overall, the more measurements there are, the lower the error, with a few exceptions (e.g., stations TRWZ, S001). The widest 95% confidence interval ($\sim 24^\circ$) is for station PLWZ. These small confidence intervals emphasize reliability of the shear wave splitting results.

In the Western and Central Basin regions, there was general agreement between

measurements made for earthquakes above and below 30 km. The average of the mean fast directions within the Western and Central Basin regions were within 10° and 14° , respectively, when comparing measurements using earthquakes above and below 30 km. (Figure 3.3b and supporting information Figure 8.1). This suggests a similar source of seismic anisotropy for earthquakes in both depth intervals and thus that the anisotropy measured is shallow. With an average raypath of 15 ± 5 km and an average regional delay time of 0.15 s, we calculate the strength of anisotropy to be $3.7 \pm 1.2\%$, which agrees with the Gledhill and Stuart (1996) estimate of 4% for the region. If shear waves encountered a deeper region of anisotropy that differed in orientation from those near surface, then the shear waves were likely resplit at the near surface (Crampin and Lovell, 1991) Therefore, we consider the entire set of earthquakes in our further discussions.

In the Western and Eastern regions, the mean fast orientations trend NE-SW to ENE-WSW, approximately parallel to the strike of the major faults in the Australian plate, such as the Wairarapa fault, and to the depth contours of the subducted plate (Figure 3.3b and c and Table 1). In contrast, in the Central Basin region, the mean fast direction orientations trend NW-SE, approximately perpendicular to these faults and to fast orientations in the other regions. Of note is station S022 (highlighted red dashed line) (Figure 3.3b), which is near the Wairarapa fault. This station showed a significant population of fast directions parallel and perpendicular to the Wairarapa fault. This effect is not present at other stations (S021, S023, LTN6, S039, and HOWZ: high-lighted red) (Figure 3.3b and Supporting Information Figure 8.2) along the Wairarapa fault and is therefore considered to be a localized effect.

3.5.2 Focal Mechanisms

Using NonLinLoc (Lomax et al., 2000), 384 earthquakes were located with a mean standard deviation (STD) of 0.32 and 0.38 km in the horizontal and 0.62 km in the vertical. We used 384 events as inputs for the Bayesian focal mechanism method of Arnold and Townend (2007). Based on the two quality control parameters used in this study, 334 focal mechanisms were deemed appropriate for the stress inversion process. Of these, 314 were located in the subducted plate (Figure 3.4b) based on the plate interface position from Williams et al. (2013). Only focal mechanisms located in the subducting plate were used in the subsequent stress inversion, because of the lower number of shallow earthquakes.

In terms of standard rake conventions (see Figure 3.4), the calculated focal mechanisms consisted of 181 normal, 30 reverse, and 103 strike-slip earthquakes. Normal faulting is dominant in the subducting plate, comprising $\sim 58\%$ of the earthquakes detected.

Western	N	$\mu(\phi)$	95%	Central Basin	N	$\mu(\phi)$	95%	Eastern	N	$\mu(\phi)$	95%
HOWZ	36	31.315	17.081	LE2	312	41.377	8.028	LE3	364	64.73	6.537
LTW1	476	89.362	3.356	LE4	3	64.333	4.439	MSWZ	39	73.002	7.839
LTW2	936	15.87	2.719	LTN6	36	22.461	6.611	PAWZ	33	69.956	9.729
LTW3	1,076	36.995	1.637	S010	792	77.8	8.097	PLWZ	15	72.494	24.504
S023	148	46.261	4.189	S014	144	66.49	5.814	S001	171	7.546	23.343
S025	712	85.133	2.764	S015	556	4.038	9.729	S002	268	80.529	10.254
S026	280	42.773	15.895	S016	196	48.727	11.76	S003A	192	29.907	13.669
S027	488	4.273	8.425	S017	60	4.579	23.767	S003	39	23.957	16.554
S028	404	84.126	7.949	S018	448	57.236	8.795	S004	376	18.252	16.976
S029	160	57.736	12.366	S019	260	70.952	5.174	S005	86	55.411	14.532
S030	212	53.255	6.584	S020	93	88.562	16.28	S006	105	81.936	4.416
S031	176	14.049	5.935	S021	246	53.956	15.412	S007	60	84.781	11.174
S032	168	70.456	4.202	S022	220	72.887	7.098	S008	153	55.096	8.616
S033	52	59.904	10.639	S040	80	3.291	9.52	S009	116	59.58	6.437
S037	508	55.091	19.601	S043	88	33.353	10.397	S012	268	81.318	5.153
S039	1172	82.881	7.114	S044	580	12.249	5.502	S013	272	53.564	3.045
WAIK	116	51.413	4.896					TRWZ	16	65.113	16.725

Table 3.1: Average splitting measurements for each station in the Western, Central Basin, and Eastern regions shown in Figure 3.3b. Note: columns 1, 5, and 9 denote which region each station resides. N: number of measurements within the shear wave window (35°) and $\mu(\phi)$: circular mean of the fast direction (relative to north). Columns 4, 8, and 12 indicate the 95% confidence interval for circular mean fast direction orientation.

Table 3.2: Information of Clusters Used in Stress Inversion and the Resulting Stress Regime and SHmax Orientation (Degrees East from North)

Region	Color	Size	Stress ratio	SHmax mean
Western	Light blue	155	0.37 ± 0.13	53.13 ± 16.72
C. Basin	Purple	99	0.60 ± 0.13	36.51 ± 16.72
Eastern	Yellow	40	0.52 ± 0.28	158.17 ± 29.41

Note. Size of cluster indicates the number of focal mechanism used in each cluster. $\pm$ signs indicate the bounds of the 95% confidence interval for stress ratio and SHmax mean.

3.5.3 Stress Inversions

We grouped 294 focal mechanisms into two sets of clusters for stress inversion, one set comprising 20 clusters with an average of 16 focal mechanisms per cluster (supporting information) and the other set comprising 3 clusters, with an average of 98 focal mechanisms per cluster (Figure 3.4 and Table 2). For each cluster, the best fit S1, S2, and S3 are contoured by probability density and are presented with posterior mode and mean values for the three principal stress orientations, and the SHmax orientation (Figure 3.4c).

Table 2 presents the number of focal mechanisms used in each cluster and the resulting SHmax orientation and corresponding 95% confidence interval, for the Bayesian inversion (Arnold and Townend, 2007). The stress inversions done in the Western and Central Basin regions give similarly tight 95% confidence intervals for mean SHmax. Given the lower occurrence of earthquakes and mixture of focal mechanisms in the Eastern region of the study area (Figure 3.4b), the cluster there is associated with larger confidence intervals and less constraints than either of the other two clusters. Overall, the tight constraints for the components of stress indicate the dependability of the stress inversion results. In order to further refine the orientations in the stress field a more refined clustering technique was done using nearest neighbor k-means, resulting in 20 clusters and 20 stress inversions. The results can be found in the supporting information.

The stress regimes of the three clusters showed some variation, but the three inversions yielded vertical or subvertical S1 and horizontal S2 and S3, denoting a normal faulting stress regime (Figure 3.4c). The stress inversion located in the Eastern region shows less constraint on S1, S2, and S3, as well as a change of the S2 and S3 orientations to NNW and ENE trend, respectively. The change of the orientations of the principal stresses in the Eastern region is highlighted by the elevated occurrence of strike-slip focal mechanisms in this region (Figure 3.4b). Of note is the slight difference in the

stress ratio between the Western ($0.37 \pm .13$) and Central Basin region ($0.60 \pm .13$). A low stress ratio would indicate that S_2 is closer to S_1 than to S_3 ($S_1 > S_2 >> S_3$), while a high stress ratio indicates S_2 is closer to S_3 than S_1 ($S_1 >> S_2 > S_3$).

There is a general agreement between the SHmax directions in this study and the available previous determinations by Townend et al. (2012). SHmax has a clear NE-SW trend within the Western and Central Basin regions ($53.13 \pm 16.72^\circ$ and $36.51 \pm 16.72^\circ$, respectively), more-or-less parallel to the depth contours of the subducting plate (Williams et al., 2013). However, SHmax in the Eastern region have a NNW-SSE ($158.17 \pm 29.41^\circ$) trend (Figure 3.4c).

3.5.4 Gravitational Stress Field

In the Eastern and Western regions, the mean SHmax orientations for gravitational stresses induced by topography ($35.4 \pm 16.2^\circ$ and $59.4 \pm 13.7^\circ$, respectively) align parallel to the subducted slab depth contours and the strike of the Wairarapa fault, whereas in the Central Basin region, the SHmax orientation trends approximately perpendicular to the strike of the Wairarapa fault and the depth contours of the plate interface ($167.3 \pm 16.4^\circ$). In the Eastern region the SHmax orientations of gravitational stresses trend NW, similar to the Western region, but include variability, with trends in a WNW and W orientation, due to topography including the Aorangi mountain range in the south (Figure 3.5 and Table 3).

3.5.5 Comparison of Methods

Of the methods presented in this study (shear wave splitting, focal mechanism inversion, and gravitational stress estimation) only the inversion of focal mechanisms are a direct measure of in situ stress, and thus the most reliable. Shear wave splitting fast directions are assumed to align with the orientations of the principal axes of stress, and gravitational stresses are vertical averages (top 25 km) based on long wavelength topography and models of crustal structure (tens of kilometers scale). The long wavelength features of the depth-averaged gravitational stress field are likely to be robust because the sources of these stresses are well constrained, but there may be significant short wavelength perturbations due to smaller scale variations in topography and crustal structure.

Figure 3.6 illustrates the robustness of the data calculated throughout this study, showing relatively small 95% confidence intervals for the three methods in each of the three regions of the study area. The exception is the shear wave fast direction in the Central Basin, which has a 95% confidence interval of $\sim 70^\circ$ (Table 3.4). The larger confidence interval is not due to a lack of coverage or data, but from the bimodal distribution of the mean fast directions in the region (Figure 3.3c) the reason for this remains unclear. In the Western region, the three measurements are oriented NE-SW. The Central Basin region yields variations between the three calculated orientations:

Table 3.3: Orientation of the Maximum Horizontal Compressive Stress (SHmax) Due To Gravitational Loading at Each Station Calculated via Nearest Neighbor

Western	GS SHmax	Central Basin	GS SHmax	Eastern	GS SHmax
HOWZ	85.15	LE2	16.261	LE3	34.225
LTW1	71.399	LE4	47.266	MSWZ	13.475
LTW2	63.504	LTN6	14.82	PAWZ	47.37
LTW3	30.816	S010	37.966	PLWZ	20.39
S023	23.812	S014	58.36	S001	45.349
S025	31.089	S015	43.85	S002	8.4299
S026	44.902	S016	00.95	S003	33.48
S027	44.902	S017	12.43	S003A	59.529
S028	46.404	S018	22.74	S004	15.774
S029	80.017	S019	21.91	S005	26.74
S030	58.204	S020	39.38	S006	78.768
S031	66.076	S021	19.505	S007	31.58
S032	34.911	S022	14.029	S008	68.529
S033	86.137	S040	44.39	S009	48.327
S037	62.208	S043	30.417	S012	46.63
S039	31.32	S044	32.44	S013	47.372
WAIK	69.47			TRWZ	47.266

Note. Columns 1, 3, and 5 correspond to the Western, Central Basin, and Eastern regions. The orientations are presented for stations where a mean fast direction was calculated. An estimate of the errors associated with SHmax from gravitational stresses would be approximately $\pm 10^\circ$ based on the wavelength of the major topographic features.

Figure 3.5: (a) Map of SHmax from gravitational stresses including $\pm 10^\circ$ error based on wavelength of topography. Orientations of SHmax in the Western and eastern regions align roughly parallel to strike of the mountain ranges and the range-bounding faults, whereas in the Central Basin region, orientations are more perpendicular to the ranges. (b) Rose diagrams displaying the orientations of the mean SHmax from gravitational stresses. Rose diagrams illustrate the spread of the mean SHmax orientations in the Central Basin and Eastern regions.

Figure 3.6: Map of (a) mean orientations and 95% confidence interval of splitting fast directions (yellow), SHmax from gravitational stresses (blue), and the general trend of principal axis of compression (thick black line) (adapted from geodetic measurements in Lamb and Vella (1987)) and (b) SHmax from focal mechanism inversion (green). Thin black lines within the 95% confidence interval indicate the mean value of the measurements. Red contours and grey faults as in Figure 3.1.

SHmax from focal mechanism inversion NE-SW; fast direction from splitting NW-SE; and SHmax from gravitational stresses NNW-SSE. The Eastern region displays a return of an approximate NE-SW orientation for SHmax based on gravitational stresses and fast direction of splitting. SHmax from focal mechanism stress inversion rotates to a NNW-SSE orientation, oblique to the trend of the plate interface depth contours.

3.6 Discussion

3.6.1 Stresses in the Subducted Pacific Plate

The SHmax orientations calculated from focal mechanism inversion within the slab are parallel to the strike of the subducting plate and margin in the Western and Central Basin regions, becoming more perpendicular in the Eastern region (Figure 3.4c). The stress orientations are associated with abundant normal and strike-slip faulting in the subducting plate in the Western and Central Basin regions of the subduction zone (Figure 3.4b). These results corroborate those of Reyners et al. (1997), McGinty et al. (2000), Du et al. (2004), and Reyners and Bannister (2007), who found focal mechanisms that ranged from strike-slip to normal within the subducting plate.

Bending of the subducting plate results in outer-arc extension above the neutral plane of the plate, and compression beneath the neutral plane (e.g. Buffett and Becker,

2012). Previously, Frepoli et al. (1996) showed an in-plane compressional stress regime in the subducting slab in the Southern Tyrrhenian subduction zone for depths ranging from 45 to 165 km. These findings have been further confirmed by detailed numerical modeling done by Babeyko and Sobolev (2008), which have an in-plane maximum compressive stress regime for depths ranging from 40 km to 100 km. In New Zealand, Arnold and Townend (2007) found an in-plane compressional stress regime northwest of the southern North Island at depths between 100 and 200 km. With the few deep earthquakes in this study we are unable to detect the deeper compressional stress regime. Nonetheless, the abundance of normal faulting in the upper 50 km of the plate suggests that bending stresses are an important cause of deformation there.

We contend that the abundance of collocated normal and strike-slip faulting in the subducted slab of the southern Hikurangi Margin is due to the oblique nature of the subduction; thus, the stress field in the subducted slab is driven both by bending of the slab (normal events) and a strike-parallel component of plate motion.

The slight change of the stress ratio between the Western (0.37 ± 0.13) and Central Basin (0.60 ± 0.13) regions suggest a variable role of the intermediate compressive stress axis (S2) in the two regions. S2 is horizontal in both regions, but relative to S1, S2 is greater in deeper section of the slab (>20 km), than it is in the shallow slab. The Western region where $S1 > S2 \gg S3$, at depths of >20 km, overlaps with Darby and Beavan (2001), Wallace et al. (2004), and Lamb and Smith (2013) affirmations that at depths of 22 km and greater (on the plate interface) there is slip occurring. Conversely, the Central Basin region where $S1 \gg S2 > S3$, at depth between 20 km and ~ 15 km, agrees with Darby and Beavan (2001) who suggested that maximum coupling occurs between 16 and 24 km depth. The greatest stress ratio is found in the Central Basin region (0.60), which is indicative of a more stable normal faulting regime. We would have expected the Central Basin to have the highest stress ratio because it is approximate to the area of the subduction plate that is experiencing the greatest amount of bending, as shown by Henrys et al. (2013) and Williams et al. (2013).

The abrupt change in orientation of SHmax below the Eastern region, compared to the Western and Central Basin regions, suggests that factors other than bending stresses control deformation within the subducting plate (Figure 3.4 and 3.6). The cluster in the Eastern region includes more strike-slip focal mechanisms, with a relatively small proportion of normal events (Figure 3.4b). The lack of normal faulting would be anticipated for a region such as the Eastern region where the curvature of the subducting plate is less (Figure 3.1). This suggests that here bending stresses play a reduced role in the total stress field.

Table 3.4: Table of Regional Mean Averages for the Orientations of the Fast Direction (FD), SHmax From Gravitational Stresses Based on Topography (GS), and SHmax From Focal Mechanism Inversion (FM)

Region	Mean FD	FD95%	Mean GS SHmax	GS95%	Mean FM SHmax	FM95%
West	65.6	± 17.65	59.4	± 7.85	53.13	± 16.72
Basin	135.7	± 35.35	167.3	± 8.20	36.51	± 16.72
East	74.4	± 11.00	35.4	± 8.10	158.17	± 29.41

Note. Columns 3, 5, and 7 show the 95% confidence intervals for their respective measurement mean direction.

3.6.2 Seismic Anisotropy

In this study there is no clear relationship between the measured delay times and the depth of earthquakes used to measure it, implying that the observed anisotropy is a shallow feature and resides in the top 30 km of the study area (Figure 3.3a). Furthermore, using the same splitting measurements to develop anisotropic delay time tomography, Wilson (2016) found that the change in delay times across the region is not reflected by change in strength of anisotropy. Furthermore, the similarities between the SHmax from gravity and shear wave fast direction (Figure 3.6a) suggest a correlation. We, therefore, suggest that the observed anisotropy is a consequence of stress-controlled closure of cracks (Crampin, 1994) in the crust of the upper Australian plate. It should be noted that the results in this study do not negate the possibility of the crust itself (i.e., rock type and faults) contributing to some portion of the shear wave splitting.

3.6.3 Comparing Stress Orientations by Region

Figure 3.6 and Figure 3.4 show the relationship between the mean fast directions, SHmax from focal mechanisms within the subduction zone, and the orientation of SHmax from gravitationally induced stresses in the Western, Central Basin, and Eastern regions. There is varying agreement between the three types of measurements across the study region, implying that there may be multiple sources contributing to the stress field in the southern Hikurangi subduction system. Figure 3.7 gives a cartoon summary of the individual orientations of these potential sources, such as gravitational stresses (Figure 3.7a), tectonic loading (Figure 3.7b), and bending stresses (Figure 3.7c).

In the Western region, there is clear agreement between the three averaged orientations (Figure 3.6 and Table 3.4). In the upper plate the fast direction is $65.6 \pm 17.65^\circ$ and gravitationally induced SHmax is $59.4 \pm 7.85^\circ$, while in the subducting plate, SHmax determined by stress inversion is $53.13 \pm 16.72^\circ$. SHmax orientations determined by

Figure 3.7: Cartoon displaying the extensional and compressional contribution to the total stress field from gravitational stresses (map view), tectonic loading (map view) (see Figure 3.6 caption), and bending stresses (map view and vertical cross section), perpendicular to the strike of the subduction trench. Blue arrows indicate extension or contraction due to gravitational stresses. Black arrows (outside) tectonic loading show orthogonal components of the Australian plate rotation; black arrows (inside) indicate the trend of the principal axis of compression. Green arrows indicate axis of extension above the midline and compression below the midline of the subducting slab. Horizontal and vertical cross sections are approximately perpendicular to plate interface depth contours and the subduction margin.

the three methods, in this region, are NE-SW. In this region it is not possible to distinguish between bending stresses and gravitational stresses. Importantly, neither of these directions is parallel to the direction of tectonic stress loading, determined from the geodetic data, which is more nearly E-W (Figure 3.6) (Lamb and Vella, 1987; Beavan and Haines, 2001; Lamb and Smith, 2013; Lamb, 2015). This could mean that tectonic loading plays a relatively small role in the Western region, compared to bending and gravitational stresses, in determining the stress field. One reason for this could be that the region is in an early part of the earthquake cycle—for example, after rupture on the Wairarapa fault, which last occurred in 1855 during a M8+ event—and tectonic stress loading will eventually assume a larger component of the total stress with time.

In the Central Basin region, there is a divergence between the three types of measurement for stress orientations (Figure 3.6 and Table 3.4). As in the Western region, SHmax orientations here, from focal mechanisms, trend NE-SW ($36.51 \pm 16.72^\circ$) in the subducted slab. But shear wave splitting fast directions are NW-SE ($135.7 \pm 35.35^\circ$) and SHmax orientations calculated from gravitational stresses are subparallel ($167.3 \pm 8.2^\circ$) to the splitting fast directions. Based on this, the splitting in this region may be more greatly affected by upper plate gravitational stresses than the bending stress within the underlying subducting slab.

The Eastern region again shows a divergence of stress orientation measurements, but in a different manner than in the Central Basin region. The orientation of SHmax from focal mechanisms within the subducting slab is NNW-SSE ($158.17 \pm 29.41^\circ$), but the orientation of SHmax from gravitational stresses is NE-SW ($35.4 \pm 8.1^\circ$), subparallel to the ENE-WSW ($74.4 \pm 11.0^\circ$) seismic fast directions (Figure 3.6 and Table 3.4). The NNW-SSE orientation of SHmax from within the subducting slab is $\sim 45^\circ$ to the plate interface depth contours here, in contrast to its trench-parallel nature in the Western and Central Basin regions. The fast direction orientations again suggest some gravitational control. Tectonic stress orientations are perpendicular to those from gravitational stresses and may contribute to the rotations measured by anisotropy and focal mechanisms.

3.7 Summary

In this study, we analyze the stress field above and below the locked part of the plate interface in the southern part of the obliquely subducting Hikurangi Margin, North Island, New Zealand.

Using new data from the 50 temporary SAHKE stations and 16 permanent GeoNet stations, we derive the orientation of the stress field for clusters of earthquake focal mechanisms and from seismic anisotropy, using 314 and 425 earthquakes, respectively. In addition, we calculate the gravitational stress field as a consequence of topography and crustal structure.

We distinguish between stresses in the lower subducting Pacific plate (determined from stress inversion of focal mechanisms) and upper overriding Australian plate (determined from shear wave fast directions).

In the northwest of the study region, where the plate interface is at a depth of 20–30 km, the orientation of SHmax from focal mechanism inversion, shear wave fast direction, and gravitational stresses are all NE-SW, parallel to the margin and the depth contours of the plate interface. In the Central Basin region, where the interface is at a depth of 15–20 km, there is clear difference between stresses in the upper and lower plates of the subduction margin, where in the upper plate stresses are orientated orthogonal to the margin, while in the lower plate, stress are orientated parallel to the margin. In the Eastern region, where the plate interface is at a depth 10–15 km, the orientation of the stress field differ in the upper and lower plates, possibly due to the addition of tectonic loading.

We interpret the stress orientations in the Western and Central Basin regions as resulting from bending stresses above the midline of the subducting slab (Figure 3.6 and 3.7). We interpret the abrupt change in the orientation of the stress field from the Central Basin to the Eastern region as a boundary in the subducting slab where bending stresses become minimized. The similarity between the stress field in the subducting and the overriding plate, as well as gravitational stresses, in Western region make it difficult to determine if the subducting plate is influencing the overriding plates stress field. In the Central Basin and Eastern region the gravitational stresses and the shear wave fast direction orientations indicate that gravitational stresses may be largely influencing the stress field of the upper plate (Figure 3.6 and 3.7). The variation in stress orientations in the Eastern region is most likely the result of tectonic stress loading due to oblique plate convergence at the subduction margin (Figure 3.6 and 3.7).

3.8 Acknowledgements

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Chapter 4

Illumination of Deformation by Bending Stresses within the Southern Hikurangi Double Benioff Zone

4.1 Abstract

Double Benioff zones are ubiquitous in subduction systems worldwide, but the stresses acting on them are not well known. We characterize stress orientations in the upper and lower bands of a double Benioff zone of the southern Hikurangi margin, New Zealand. Stress orientations were calculated from focal mechanisms with 10 or more polarity picks, using a Bayesian stress inversion technique. In the deeper region of the subduction zone, the stress orientations in the upper band of seismicity are consistent with an extensional stress regime, whereas stress orientations within the lower band of seismicity are consistent with a compressional stress regime. In the shallow region of the subduction zone, the inversion of the upper and lower band of seismicity are consistent with extensional stress regimes. This demonstrates that deep in the subduction zone bending stresses are dominant, whereas in the shallow portion of the subduction zone, slab-pull forces are dominant.

4.2 Introduction

Benioff zones provide the most direct evidence for the existence of subducting slabs. The nature and distribution of seismicity within Benioff zones provide constraints on the rheology and stresses in a subducting slab. It is important to characterize these constraints as they can enhance our understanding of deformation, strain partitioning, and the generation of mega-thrust subduction earthquakes. Hasegawa et al. (1978)

was first to characterize two distinct bands of seismicity within a Benioff zone, referred to as a 'double Benioff zone', located in northeastern region of Honshu, Japan. Double Benioff zones (DBZs) are ubiquitous within subduction zone systems worldwide (Brudzinski et al., 2007). The upper band of seismicity has been interpreted as the faulting of dehydrated and/or metamorphosed upper oceanic crust, whereas the lower band is thought to be faulting of the dehydrating upper mantle (i.e., serpentinized peridotite and antigorite) (Kirby et al., 1996; Peacock, 2001; Yamasaki and Seno, 2003; Zhang et al., 2004; Brudzinski et al., 2007).

The dynamics of stresses acting within the subducting plate resulting in a DBZ are not well understood. Some DBZ studies show down-dip extension in the upper and down-dip compression in the lower band (Engdahl and Scholz, 1977; Hasegawa et al., 1978; Kawakatsu, 1985; Kao and Chen, 1994; Brudzinski et al., 2007). In contrast, Abers (1992); Ratchkovsky et al. (1997); Slancová et al. (2000); Christova and Scholz (2003); Rietbrock and Waldhauser (2004); Brudzinski and Chen (2005) observed down-dip extension in both the upper and lower bands of seismicity within various DBZs.

New Zealand provides a favorable opportunity to investigate DBZs because it can be studied from land-based seismic arrays. Benefiting from a dense land based temporary and permanent deployment; this study aims to characterize the stresses present within the southern Hikurangi DBZ, by performing a high-resolution stress inversion analysis.

4.3 Southern Hikurangi Margin

East of central New Zealand, the Australian and Pacific plates converge at ~ 38 mm/yr (Figure 4.1; Beavan and Haines, 2001; Beavan et al., 2002). Convergence results in the westward oblique subduction of Pacific plate under the Australian plate. Langridge et al. (2005) calculated that 60 to 90% of margin-parallel motion is accommodated by faults in the Australian plate, while Wallace et al. (2009) proposed that margin-perpendicular motion is accommodated by episodic slip (100s to 1000s of years) on the subduction thrust. The rate of subduction along the length of North Island is not uniform (Walcott, 1984; Reyners, 1998; Wallace et al., 2004, 2009, 2012). There is a slip deficit of 20 - 30 mm/yr along the plate interface beneath the southern North Island (Wallace et al., 2004). The slip deficit region is thought to represent where the overriding Australian plate and the subducting Pacific plate are 'partially locked' or 'coupled' at the plate interface. Darby and Beavan (2001) calculated the depth of the maximum-coupled zone to be between 15 and 24 km, using 10 years of campaign GPS data. Lamb and Smith (2013) using cGPS (up to 2009) data calculated a similar maximum coupling depth at ~ 25 km.

Figure 4.1: Tectonic overview and station locations of seismometers (cyan triangles) used to relocate earthquakes. Red lines indicate plate/major tectonic boundaries, including North Island Seismic Belt (NISB) (Coffin et al., 1998). Grey lines show active faults (<https://data.gns.cri.nz/af/>; (Langridge et al., 2005)). Dashed lines show depth (km) of subduction plate interface (Williams et al., 2013). Black arrow shows relative plate motion between the Australian and Pacific Plates. Inset: zoomed view of southern North Island, New Zealand, showing density of seismic stations in study area.

4.4 Previous Studies

Relocated earthquakes from Eberhart-Phillips and Reyners (1997); Du et al. (2004) highlighted the existence of a Double Benioff Zone (DBZ) at the southern end of the Hikurangi margin (Figure 4.2). The discreteness of the two bands of seismicity varies along the strike of the subduction margin. In the northern South Island the bands are clearly distinguishable, while in the southern North Island, the two bands coalesce becoming harder to discern (Figure 4.2b and c). McGinty et al. (2000), using 48 upper band focal mechanisms and 12 lower band focal mechanisms, observed stress orientations consistent with down-dip extension throughout the northern South Island and southern North Island.

Figure 4.2: McGinty et al. (2000); Du et al. (2004) double Benioff zone study area and earthquake locations. a: map-view of McGinty et al. (2000) (magenta) and Du et al. (2004) (cyan) study area. b: northern and southern cross-sections of McGinty et al. (2000) earthquake locations. c: initial locations (top) and double-difference relocations (bottom) of Du et al. (2004).

4.5 Seismic Data

Seismic data were recorded on the permanent New Zealand-wide GeoNet array (up to 171 stations) and the temporary SAHKE I array (48 short-period and 2 broadband stations) that was deployed from November 2009 to March 2010 (Figure 4.1; Seward et al., 2010). During a nine-month period (September 2009 to May 2010) 678 earthquakes ($M2+$ to $M5+$) at depths 25 km or greater were detected by GeoNet, throughout the southern North Island, New Zealand (Figure 4.3).

4.6 Methods

4.6.1 Earthquake Relocation

P- and S-wave phase arrivals and first motion polarities were manually picked and located using the Seisan Earthquake Analysis Software (SEISAN) package (Havskov and Ottemoller, 1999). Initial hypocenter locations were calculated using Hypocenter (Lienert et al., 1986; Lienert and Havskov, 1995) and a southern North Island 1D velocity model (Henry et al., 2013). Final hypocenter locations were determined using NonLinLoc (Lomax et al., 2000), a non-linear location package, and a New Zealand wide 3D velocity model (Eberhart-Phillips et al., 2010).

4.6.2 Bayesian Focal Mechanism and Stress Inversion

Focal mechanisms are calculated using a Bayesian approach (Walsh et al., 2009). The Walsh et al. (2009) Bayesian method treats all hypocenter locations as probabilistic, allowing for errors in hypocenter locations, and consequently focal mechanism uncertainties, to be propagated into the final stress inversion.

The stress inversion of focal mechanism data is done using the Bayesian method outlined in Arnold and Townend (2007). This method performs a stress inversion calculation on predetermined clusters of earthquake data, returning the maximum ($S1$), intermediate ($S2$), and minimum ($S3$) compressive stress orientations as posterior probability density functions (PDFs). The maximum horizontal compressive stress (SH_{max}) orientation is calculated using the Lund and Townend (2007) method.

4.6.3 Focal Mechanism Clustering

Three clusters of earthquakes using focal mechanisms calculated using 10 or more polarity picks were classified based upon location within the subducting plate: (1) earthquakes located in the upper half of the seismogenic zone (i.e., plate interface to the neutral plane) and (2 and 3) earthquakes within the lower half (i.e., neutral plane to bottom of seismogenic zone) of the seismogenic zone (Figure 4.3). The lower half of seismicity is split into two individual clusters, based on the initiation of reverse faulting (at ~ 130 km, see Figure 4.4). The plate interface used was determined by Williams

Figure 4.3: Map view and cross-sections of relocated earthquakes, colored by depth, using a 3D (Eberhart-Phillips et al., 2010) velocity model and NonLin-Loc (Lomax et al., 2000). Dashed lines indicate plate interface depth (km) between the Australian and Pacific plates. Grey lines show active faults (<https://data.gns.cri.nz/af/>; (Langridge et al., 2005)). Cross-section projected onto X to X' line. In cross section dashed lines show the plate interface (Williams et al., 2013), the neutral plane (NP) and the bottom of the seismogenic zone.

et al. (2013). The bottom of the seismogenic zone was determined visually, based on earthquake density, after the final relocation of the earthquakes. The neutral plane is identified as the plane that is halfway between the top and bottom of the seismogenic zone within the subducting plate.

4.7 Results

4.7.1 Earthquake Locations

The 675 earthquakes were relocated with a mean horizontal standard deviation of 1.80 km East-West, 0.42 km North-South, and a mean vertical standard deviation of 1.48 km. The bands of the DBZ are not well defined (Figure 4.3). These results are similar to those presented by McGinty et al. (2000) and Du et al. (2004), in that below the southern North Island, the bands of seismicity in the DBZ are less defined, than those to the south. The consolidation of the bands of seismicity is likely due to the lack of depth constraints, resulting from the lack of stations to the NW and directly above the DBZ (Figure 4.1).

4.7.2 Focal Mechanism and Stress Inversion

657 of the relocated earthquakes are used as inputs for the Arnold and Townend (2007) Bayesian focal mechanism method. Based on standard rake convention (Figure 4.4), there are 308 normal, 116 reverse, and 223 strike-slip focal mechanisms. This distribution of faulting is comparable to Evanzia et al. (2017), who found predominantly normal faulting with some strike-slip and little reverse faulting in southern North Island, using data recorded only during the November 2009 to March 2010 deployment of the SAHKE I array. Most of the normal faulting is limited to the upper band of seismicity (Figure 4.4 and 4.5). There is relatively little reverse faulting in the upper or lower band until the plate interface is at a depth of ~ 35 km (Figure 4.4). Strike-slip faulting is diffuse throughout the upper band, however it is limited in the shallower reaches of the lower band of seismicity (Figure 4.4). Reyners and Eberhart-Phillips (2009) attributed the lack of seismicity in shallower reaches of the lower band to the presence of fluids. At plate interface depths of greater than ~ 35 km there are more equal proportions of faulting within the subducting plate. The subducting slab increases from 05° to 15° dip at a plate interface depth of ~ 30 km (Henrys et al., 2013). At ~ 40 km depth, the subducting plate is juxtaposed to the crust-mantle boundary (Moho) on the Australian plate (Reyners and Eberhart-Phillips, 2009; Henrys et al., 2013). The diversification of focal mechanisms at a plate interface depth of greater than ~ 35 km indicates a shift in the stress dynamics within the subducting plate.

Based on polarity picks (> 10) and location within the subducting plate, 149 focal mechanisms are used for inversion in the upper band, 43 focal mechanisms are used in the down-dip lower band, and 11 focal mechanisms are used in the up-dip lower band

Figure 4.4: Focal mechanism solutions derived using the Walsh et al. (2009) Bayesian method. 657 focal mechanisms (normal: 308, reverse: 116, strike-slip: 223) with at least one polarity pick colored by style: normal ($30^\circ < \text{rake} (R) < 150^\circ$) (red); reverse ($-30^\circ < R < -150^\circ$) (blue); strike-slip ($-30^\circ < R < 30^\circ$ and $-150^\circ < R < 150^\circ$) (green). Cross sections projected onto X to X' line, as in previous figures. Grey and dashed line in cross sections show location of featured specified in Figure 4.3.

of seismicity (Figure 4.5).

The inversion of the upper band cluster (cyan) yields a vertical S1 and horizontal S2 and S3, indicating an extensional stress regime (Figure 4.5), with a SHmax orientation of $\sim 060^\circ$. The inversion of the down-dip lower band cluster yields a vertical S3 and a horizontal S1 and S2, denoting a compressional stress regime (Figure 4.5), with a SHmax orientation of $\sim 040^\circ$. The inversion of the up-dip lower band cluster yields a vertical and horizontal mixing of S1 and S2, while S3 is horizontal, indicating an extensional stress regime (Figure 4.5), with a SHmax orientation of $\sim 050^\circ$. All three SHmax orientations are sub-parallel to the relative plate motion between the Pacific and Australian plate, at the southern North Island (Figure 4.1, 4.5; DeMets et al., 1994).

Additionally, three other clusters are generated based upon position within the plate, but regardless of polarity pick numbers: upper band cluster (434 focal mechanisms), down-dip lower band cluster (132 focal mechanism), and up-dip lower band cluster (93 focal mechanism). Inversion results of the three additional clusters show similar results and can be found in supplemental material (Appendix B Figure 3). This indicates that the observed stress orientations are an authentic feature of the DBZ and not an artefact of cluster criteria.

4.8 Discussion

4.8.1 Upper Band Stress Orientations

Here, as in previous studies (McGinty et al., 2000; Evanzia et al., 2017), the stress orientations in the upper band are indicative of an extensional stress regime with down-dip extension; where S1 is near vertical and S3 is oriented in the direction of the dip (Figure 4.5, Appendix B Figure 1, 2).

4.8.2 Lower Band Stress Orientations

The compressional stress regime calculated from the down-dip cluster of lower band seismicity in this study (Figure 4.5, Appendix B Figure 1, 2) differs from those calculated by McGinty et al. (2000), who found the lower band of seismicity exhibited a down-dip extensional regime, throughout the southern North and northern South Island.

The differences between observations of this study and McGinty et al. (2000) suggests that the 12 focal mechanisms in McGinty et al. (2000) were insufficient to observe the shift in stress dynamics within and along strike of the subduction margin. Although different stress regimes within the lower band of a DBZ are not unique to the southern Hikurangi margin (e.g., Nazca and Aleutian: see Table S1 in Brudzinski et al. (2007), this study's area of interest is encompassed by the region McGinty et al. (2000) characterized. Additionally, unlike the studies referenced in Brudzinski et al. (2007),

Figure 4.5: Clusters of focal mechanisms with at least 10 polarity picks used as inputs into the Bayesian stress inversion method from Arnold and Townend (2007). Red-dashed line indicates approximate of the Moho (Henry et al., 2013). Upper cluster (149 focal mechanisms) shown by cyan circles, down-dip lower (left) cluster shown by magenta circles (43 focal mechanisms) and up-dip lower (right) cluster shown by orange circles (11 focal mechanisms), mapped on X to X' cross-section from previous figures. Stereonets show azimuth of maximum principal stress (S1), intermediate principal stress (S2), and minimum principal stress (S3), shown as the posterior probability density functions (PDFs). The best fitting maximum horizontal stress (SHmax) shown as a dashed line. Black arrows indicate plate convergence direction. Dashed line in cross sections show location of featured specified in Figure 4.3.

Table 4.1: Adapted from Brudzinski et al. (2007) Supplemental Figure 1. Describing features of DBZ studies done in different locations on the same subduction system. Note: DDE (down-dip extension), DDC (down-dip compression), and DOC (dip-oblique compression). 'New Zealand' indicates this study's results.

Location	Longitude (W°)	Latitude (N°)	Plate Age Age (ma)	Events (#)	Slab Dip (°)	Upper Band	Lower Band
New Zealand	-7.5	-42.5	90	48	12	DDE	DDE
<u>New Zealand</u>	-6.5	-40.75	90	434	225	DDE	DOC/DDE
Nazca	-73.4	-34.5	33	39	22	DDE	DDE
Nazca	-71.4	-24.4	43	176	15	DDE	DDE
Nazca	-75.8	-15.7	38	71	3	DDE	DDC
Aleutian	-161.2	53.6	55	25	49	DDE	DDE
Aleutian	-179.8	50.5	56	87	36	DDE	DDC

this compressional regimes shortening orientation is oblique to the dip direction (Figure 4.5). This is likely to be due to the oblique nature of subduction at the southern Hikurangi margin. The compressional stress regime could result from the bending of the subducting Pacific plate (e.g. Buffett and Becker, 2012).

4.8.3 Stress Orientations in Double Benioff Zones

In a global context, subducting slabs (e.g., Nazca, Aleutian, New Zealand: in this study) that show variation in stress orientations in the lower band of seismicity also have a lower subduction dip angle (Table 4.1; Brudzinski et al., 2007). The rate of change of the subduction dip in the southern North Island is greater compared to most of the northern South Island (Appendix B Figure 1). Extension in the upper band and compression in the lower band is indicative of bending forces (Buffett and Becker, 2012).

Bending moment (M) is defined as (Watts, 2001), where (E) is Young's modulus, (H) is elastic plate thickness, (ν) is Poisson's ratio, and (R) is the radius of curvature:

$$M = -\frac{EH^3}{12(1-\nu^2)R} \quad (4.1)$$

Based on slab dips in the southern North Island and the northern South Island (Appendix B Figure 1, 2), a Young's modulus (E) of 2×10^{11} N/m² (Cohen and Darby, 2003), elastic plate thickness (H) of 4.5×10^4 m, Poisson's ratio (ν) of 0.235 (Eberhart-Phillips et al., 2005), and the radius of curvature (R) of 1.49×10^5 m and 2.25×10^5 m, respectively (Appendix Figure 2), bending moment (M) is -1.079×10^{19} N/m² for the southern North Island and -7.415×10^{18} N/m² for the northern South Island. The

greater bending moment in the southern North Island, compared to southern South Island, further confirms the bending stresses are present, as shown by the stress inversions. Assuming McGinty et al. (2000) accurately characterized the stress orientations in their area of interest (Appendix B Figure 1); overall slab-pull forces are dominant within the subducting Pacific plate at the southern Hikurangi Margin. Given the subduction dip changes and the coeval bending stresses observed in this study, it is likely McGinty et al. (2000) had insufficient focal mechanisms to differentiate between areas where bending and slab-pull stresses are dominant.

As previously stated, the two bands of seismicity of the double Benioff zone are more distinct and separated below the northern South Island, than they are below the southern North Island (Figure 4.2). As shown in Appendix Figures 9.1 and 9.2, the region of the subducting plate below the southern North Island is experiencing more bending forces than the region below the northern South Island. As a result of the bending forces, the subducting plate below the southern North Island is likely experiencing a loss in elastic strength causing increased faulting and thus increase dehydration. This may be one reason for the abrupt onset of reverse faulting and the coalescing of the band of seismicity in the down-dip section of the subducting plate below the southern North Island (Figure 4.4).

The key observation is that the DBZ with division of upper and lower bands of contrasting stress patterns is confined to the Hikurangi margin beneath the southern North Island. We suggest that subduction in southern North Island beneath the 150 km thick lithosphere of the overriding Australian plate, with the absence of an asthenospheric wedge (Stern et al., 2006; Dimech et al., 2017), may have promoted stronger bending here by forcing the Pacific Plate more strongly downwards with a smaller radius of curvature. This way, stresses from bending rather than slab pull dominate the stress regime in this region.

4.9 Conclusion

In the deeper region of the subduction zone the upper band of seismicity within the southern Hikurangi DBZ is indicative of down-dip tension, while the lower band shows compression (Figure 4.5 and 4.6). In the shallow region of the subduction zone, down-dip tension is observed in both the upper and lower bands of seismicity. We interpret the upper extensional and lower compressional stress regimes, of the deep subduction zone, as a result of the bending of the subducting Pacific plate (Figure 4.5 and 4.6). The bending stresses we observe may result from the interaction between the subducting Pacific plate and the overly thickened Australian lithosphere. Based on the observations of this study and the slab dip geometry (Williams et al., 2013), north of the study there should be even greater bending forces. We interpret the upper and lower extensional stress regimes, of the shallow subduction zone, as a result of the slab-pull

forces (Figure 4.5 and 4.6). Globally, the magnitude of deformation within subducting plates by bending stress is dependent on initial dip of the subducting plate and the rate at which the dip angle increases. As subduction dip characteristics are unique to subduction systems globally, and can vary within individual subduction zones themselves, the dynamics of stress controlling DBZ faulting distribution are likely equally variable.

4.10 Acknowledgements

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Figure 4.6: Cartoon (not to scale) of the distribution of extensional and compressive stress regimes within the subducting Pacific beneath the southern North Island and beneath the northern South Island, New Zealand. (Left) Red-lines indicate cross-section locations. (a): Above the neutral plane extension is pervasive, whereas below the neutral plane, compression dominates. The stress state within the subducting slab is the result of rollback of Pacific plate (black arrow). (b): Above and below the neutral plane extension is dominant (McGinty et al., 2000). The stress state within the subducting slab is the result of slab pull (black arrow). Grey and the red dashed lines approximate the location of local active faults (<https://data.gns.cri.nz/af/>). Black lines indicate plate/major tectonic boundaries, including North Island Seismic Belt (NISB) (Coffin et al., 1998). Black dashed line shows cross-section location.

Chapter 5

Stress and Structure Controlled Anisotropy Revealed by a High-Density Seismic Transect Across Southern North Island, New Zealand

5.1 Abstract

Local earthquakes recorded on an array of 291 seismic stations placed 300 m apart are used to examine seismic anisotropy across the southern North Island, New Zealand. The high-density array provides a unique opportunity to gain in depth knowledge of seismic anisotropy from local earthquakes. We calculated shear-wave splitting measurements on 142 stacks composed of traces from five adjacent seismic stations on 21 local earthquakes. The resulting splitting measurements showed no dependence of fast azimuth and delay time on back azimuth, station-event distance, or angle of incidence. The average ($\pm$ 95% confidence interval) fast azimuth trended N-S ($18^\circ \pm 12$) west of the Wellington fault. Between the Wellington and Wairarapa faults, the average fast azimuth trended NNE-SSW ($65^\circ \pm 12$). The average fast azimuth trended NNW-SSE both in the Wairarapa basin ($-37^\circ \pm 11$) and east of the Wairarapa basin ($08^\circ \pm 10$). The average delay time across the study area was $0.175 \text{ s} \pm 0.014$. We conclude the anisotropy observed west of the Wairarapa fault is derived from local fault structures. East of the Wairarapa fault we conclude the fast azimuth is due to stress-aligned micro cracks in the upper 15 km of the Australian plate and that the fast azimuth is parallel to the orientation of maximum horizontal compression direction (SHmax). We interpret the variation we see in the south-eastern section of the study region as the result of

a change in relative amplitudes of the three principal stress axes due to an increased influence from gravitational and tectonic loading stress.

5.2 Introduction

The stress field is one of the principal controlling factors on a region's earthquake faulting processes (Kusznir et al., 1991; Zoback, 1992; Townend et al., 2012). Parameters of the stress field can be measured using a variety of methods including but not limited to borehole measurements, focal mechanism inversion, and shear-wave anisotropy. Yet, these measurements are usually only available in low resolution (10's of kms) due to the station spacing of typical seismic studies. The objective of this study is to examine in high resolution how the anisotropy, and therefore the stress field, evolves across the southern North Island, New Zealand.

Previous passive seismic experiments in New Zealand (e.g., Wilson et al., 2004; Harrison and White, 2006; Seward et al., 2010; Thurber et al., 2012, etc.), have used arrays with station spacing of 10s km or have been confined to a small study area. Making use of data collected during a dense array deployment allows for the unique opportunity to analyze earthquake data on a large number of closely spaced (100s m) seismic stations, while implementing methods (i.e., station stacking) usually reserved for active source experiments.

5.2.1 SAHKE II Experiment

We use earthquakes recorded on all available 291 short-period 3-component stations spaced approximately every 300 m (some 150 m) across the southern North Island, New Zealand (Figure 5.1). These stations composed a third (two-thirds were vertical component stations only) of the SAHKE II deployment, which was the second phase of a two-phase seismic experiment designed to investigate the characteristics of the subduction zone interface beneath the southern North Island (Henrys et al., 2013). The SAHKE experiment, phase-one (I) and phase-two (II) was a collaborative effort between GNS Science, Victoria University of Wellington, University of Tokyo, Japan (Earthquake Research Institute), and the Ministry of Economic Development, Crown Minerals. During the active portion of the SAHKE II experiment, the stations were left recording for 6 - 8 hours each day for six days (March 9th - 14th 2011), for the purpose of collecting earthquake data.

Although the stress field of the southern North Island has been previously examined at a regional scale (Townend et al., 2012; Evanzia et al., 2017), this study is uniquely capable of tracking changes in the anisotropy and stress field orientations with high precision, due the amount (291) and density (300 m and/or 150 m spacing) of the SAHKE II stations (Figure 5.1).

Figure 5.1: SAHKE II array and Tectonics. Location of 142 stacks of 291 high frequency seismic stations (green circles - appears as green line). 21 earthquakes (red, white, and blue circles) colored by depth are used as sources for this anisotropy study. Dashed-black lines show plate interface depth (Williams et al., 2013). Thick-black lines and grey lines show active faults (<https://data.gns.cri.nz/af/>; (Langridge et al., 2005)). Black-starred earthquake is used in Figure 5.3 and 5.5, blue-starred earthquake is used in Figure 5.4, and the red-starred earthquake is used in Figure 5.6. Map-inset: New Zealand tectonics showing location of plate boundaries (red-dashed lines, Coffin et al. (1998)) (e.g., Alpine Fault, Hikurangi Margin (HK), and North Island Seismic Belt (NISB)). Plate motion vector (Beavan and Haines, 2001). Black box indicates location of study area.

5.2.2 Shear-wave Anisotropy

Seismic anisotropy, or shear-wave splitting, is the measurement of the time delay between two polarized orthogonal shear-waves resulting from a shear-wave entering an anisotropic medium. Crustal anisotropy is thought most often to result from differential stresses preferentially closing cracks that are aligned perpendicular to the maximum principal stress direction (Nur, 1971), but can be the result of tangible geologic features (Leary et al., 1990). This micro-crack structure within the crust results in a decrease in velocity for shear-waves traversing the cracks relative to shear-waves that parallel the cracks. The relationship between shear-wave velocity and cracks translates to the shear-wave fast azimuth roughly paralleling the maximum horizontal compressive stress (SHmax) orientation (e.g., Crampin, 1994).

Geologic features that can cause shear-wave anisotropy include but are not limited to aligned rock fabric, fault structures, and sedimentary bedding planes (Savage et al., 1989; Crampin and Peacock, 2005; Leary et al., 1990). Fabric-related anisotropy can manifest throughout the crust, resulting from shearing or metamorphism, which in turn can cause the alignment of anisotropic minerals (Do Nascimento et al., 2002; Okaya et al., 2016) (Do Nascimento et al., 2002; Okaya et al., 2016). Structural fabrics would affect shear wave splitting by controlling the fast polarization azimuth of vertically propagating shear-waves (Liu et al., 2008). Because of the various geologic and tectonic features that can result in anisotropy, results of any anisotropy study need to be examined in concert with other studies.

5.3 Tectonic and Geologic Setting

The North Island, New Zealand is on the Australian side of the Australian-Pacific plate boundary. East of the southern North Island is the southern terminus of the Hikurangi margin, where the Pacific plate is obliquely subducting beneath the Australian plate at 38 mm/yr (Beavan and Haines, 2001; Beavan et al., 2002) (Figure 5.1).

Walcott (1984) and more recently others (Reyners, 1998; Wallace et al., 2004, 2009, 2012) have demonstrated that slip on the plate interface varies along the length of the Hikurangi margin beneath the North Island. Making use of high-resolution decadal campaign and continuous global positioning system (GPS) data, Wallace et al. (2004); Beavan et al. (2007) showed that the southern North Island is located over a locked zone of the plate interface, where the overriding and subducting plates are partially coupled, resulting in a slip deficit of 20 - 30 mm/yr. Adjacent to the locked zone, numerous episodes of slow slip occur on the plate interface. These slow-slip events last from weeks to months and occur offshore to the west of the study region, at depths from 30 - 60 km (Beavan et al., 2007; Wallace and Beavan, 2010; Lamb and Smith, 2013; Wallace et al., 2014).

NE-SW striking dextral strike-slip and reverse faults are the dominant tectonic on-

shore features of the southern North Island (Langridge et al., 2016, Figure 5.1). The major on-shore faults (e.g., Wellington and Wairarapa faults) accommodate 60 - 90% of margin-parallel motion (Langridge et al., 2005), whereas motion on the subduction thrust accommodates some of the margin-perpendicular motion (Wallace et al., 2012). Using retriangulated geodetic measurements Walcott (1978), and later Lamb and Vella (1987), as well as Beanland and Haines (1998), demonstrated that dextral shear is the principal form of deformation west of the Wairarapa fault, whereas east of the fault, compression is the principal cause of deformation.

In a continental context, the crust throughout New Zealand consists of various volcanic, sedimentary, plutonic, and metamorphic basement terranes (Mortimer, 2004) (Figure . The upper crust of the southern North Island is predominantly made from sedimentary terranes. The western region of the study area consists of sandy-mudstones (Rakaia Terrane), the central region (the Wairarapa basin) is made up of limestones overlaying sand and mudstones (Pahau Terrane), and the eastern region of the area, the East Coast Allochthon is predominantly ophiolitic, volcanic and sedimentary (sand and siltstones) rocks that were thrust over the southern North Island from the north-east in the late Oligocene (Begg et al., 2000; Lee and Begg, 2002; Mortimer, 2004). In the eastern region of the Rakaia Terrane, there is a minimum expression of the Haast Schist (Mortimer, 2004). It should be noted that within the the Rakaia, Pahau, and East Coast Allochthon Terranes are marked by predominantly westward steeply dipping beds, with azimuth of NE-SW (Begg et al., 2000; Lee and Begg, 2002). Although there are no known large metamorphic terranes at the surface in the southern North Island, in the northern South Island, there are mafic to ultra mafic igneous and sedimentary rocks becoming increasing schist-like towards the west (Begg et al., 2000). Based on velocity modeling, Eberhart-Phillips and Reyners (1997) identified a high-velocity (V_p 6.5 - 6.7 km/s) and relatively low V_p/V_s associated with high-grade schist in the northern South Island. Making use of shear-wave splitting azimuthal data and receiver function calculations, Savage et al. (2007) suggested the presences of dipping anisotropic body, likely blueschist, in the lower crust below the westernmost southern North Island.

5.4 Previous Studies

There have been several shear-wave splitting studies done in the southern North Island, New Zealand, which examined crustal and upper mantle anisotropy. Gledhill and Stuart (1996), using local earthquakes recorded on the temporary Tararua array, calculated a fast azimuth of $51^\circ \pm 18$ for the crust of the Australian plate and $41^\circ \pm 15$ in the underlying mantle, which is sub-parallel to the strike of the subduction zone and major crustal geological structures (Gledhill, 1991). Later, Marson-Pidgeon and Savage (1997), Marson-Pidgeon et al. (1999), and Marson-Pidgeon and Savage (2004), using teleseismic S, ScS, and SKS events, obtain similar fast azimuths (NE-SW) that were sub-parallel to the subduction zone. (Brisbourne et al. (1999); Audoin et al.

Figure 5.2: Map of major geologic terranes at the southern North Island, New Zealand. From west to east: Rakaia Terrane (yellow), Pahau Terrane (purple), and East Coast Allochthon (blue) (Mortimer, 2004). Major bedding and fault are orientated NE-SW. Minor faults, foliation, and bedding plane orientations vary throughout the terranes and in proximity to the SAHKE II array (red-dashed box) vary (see Appendix C).

(2000) determined that the anisotropy (NE-SW fast azimuth) calculated from deeper earthquakes in the region were reflective of trench-parallel flow of the mantle. Most recently Evanzia et al. (2017), using local earthquakes recorded on the SHAKE I array, observed a regional variation in fast azimuth across southern North Island. Evanzia et al. (2017) calculated a NE-SW ($65^\circ \pm 17$) fast azimuth west of the Wairarapa fault, NW-SE ($-45^\circ \pm 35$) in the central southern North Island, between the Wairarapa and Dry Creek faults, and ENE-WSW ($74^\circ \pm 11$) east of the Dry Creek fault. In conjunction with stress field observations in the subducting slab and gravitational stresses, Evanzia et al. (2017) postulated that the fast azimuths calculated in the crust resulted from the transfer of bending stresses and/or gravitational stresses in the west, predominately from gravitational stresses in the central region, and a combination of gravitational stresses and tectonic loading stresses in the eastern region of the southern North Island.

5.5 Seismic Data

The SHAKE II array was deployed for six days, recording each day for 6 - 8 hours through the late night to early morning. During these periods 21 local earthquakes ($M_L 1.4$ to $M_L 3.3$) were detected by GeoNet (<https://www.geonet.org.nz/>), ranging from depths of 5 to 56 km. Figure 5.3 shows an example of a clearly recorded earthquake on the SHAKE II array.

5.6 Shear-Wave Analysis Methods

Using GeoNet derived origin times (<https://www.geonet.org.nz/>) the 21 detected earthquakes were cut out of the SHAKE II dataset. We linearly stacked the raw seismic data for five adjacent stations aligning on the theoretical TauP software (Crotwell et al., 1999) shear-wave arrival using the ak135 velocity model (Kennett et al., 1995, Figure 5.4). To reduce the effect of one bad station measurement (if present) the stacking was done with a sliding window, where each window would have three overlapping stations (e.g. Stack 1: A, B, C, D, E; Stack 2: C, D, E, F, G; Stack 3: E, F, G, H, I). There are some gaps present in the SHAKE II array (Figure 5.3); stations juxtaposed across these gaps were not stacked. After the sliding-window stacking was performed we had a total of 142 stacks of data per event. Figure 5.5 shows an example of a recorded wave from an earthquake moving across the stacked stations from SW to NE. First arriving P- and S-phases were repicked on the stacked stations by hand using standard methods, using the Seismic Analysis Code (SAC) (Goldstein et al., 2003; Goldstein and Snoke, 2005).

We use the Multiple Filter Automatic Splitting Technique (MFAST) (Savage et al., 2010) to calculate crustal anisotropy parameters (e.g., fast azimuth and delay times) for individual stacked-event pairs. Commencing with the pre-picked S-phase arrivals,

Figure 5.3: An example of an earthquake (black star Figure 5.1) recorded on the SAHKE II array, with a bandpass filter of 4Hz to 20Hz. An offset distance of zero indicates the location of the westernmost station. The P-wave (blue) arrival can clearly be seen in the vertical component and is less continuous in the horizontal components. S-wave (red) arrival is visible along the array. In the larger offsets a secondary phase (green), possibly a reflection, can be seen after the S-wave, with possible commingling of the phases in the furthest east stations. White spaces show gaps in the array due to inaccessible terrain.

Figure 5.4: Stacked data example. Traces (blue) from five adjacent stations in the SAHKE II array, stacked (aligned on TauP theoretical S-pick) to make final trace (red). Stacked trace (red) used to pick shear-wave for use in MFAST program. Dashed line indicated shear-wave arrival.

MFAST determines the best filter for a given trace by finding the maximum product of signal to noise ratio (SNR) and bandwidth. A grid search, using the best filter and multiple measurement windows, is done over the fast azimuth and delay time parameter space to determine the two values which best correct for splitting. The best fitting fast azimuth and delay time parameters are chosen by identifying the minimum of the smallest eigenvalue for the corrected particle motion (Silver and Chan, 1991), with corrections for error bars by Walsh et al. (2013). The most stable solution is determined by the application of an unsupervised cluster analysis (Teanby et al., 2004) to the fast azimuth and delay time parameters. After the splitting analysis is complete, MFAST grades the stacked-event pair measurements from A - D, based on four criteria: (I) SNR, (II) fast azimuth and delay time uncertainty, (III) cluster uniqueness, and (IV) if the measurement is null (Savage et al., 2010; Wessel et al., 2010).

A measurement is null when the arriving shear-wave has not been split; this occurs when there is little to no anisotropy or when the particle motion of a wave traveling through an anisotropic medium is aligned parallel or perpendicular to the fast azimuth. MFAST identifies measurements as null if the delay time is within 80% of highest value in the grid search (1.0 s) or if the fast azimuth is within 20° of the incoming polarization direction or its perpendicular. Graphically, a null measurement can be identified by the presence of two narrow bands in the confidence interval of the fast azimuth. The U-shaped confidence interval allows for any amount of splitting parallel to the incoming polarization directions (Savage et al., 2010).

5.7 MFAST Splitting Results

342 A- and B-quality splitting measurements were calculated over the 142 stacks using 19 local earthquakes. Figure 5.6 shows an example of an A-quality measurement and graphically displays the processing steps taken by MFAST to calculate anisotropy parameters and measurement quality. A- and B- quality splitting measurement calculated from unstacked traces from all earthquakes, the four closest earthquakes to the SAHKE II array, five random earthquakes, and a single earthquake can be found in the Supplemental Material (Appendix C Figure S1 - S20). All splitting measurements, stacked and unstacked, give similar average splitting measurements.

Because shear-wave splitting results from local earthquakes are often scattered ((Gledhill, 1991; Zhang et al., 2007; Johnson et al., 2011; Karalliyadda and Savage, 2013; Savage et al., 2016) we investigate whether some splitting result parameters (e.g., back azimuth, delay time, fast azimuth) are dependent on one another. Density contour plots show that there are no strong correlations between splitting parameters (Figure 5.7, Appendix C Figures S4, S9, S14, S19). We see scatter associated with the fast azimuths from local earthquake sources (Figure 5.8). Because of the scatter, we are unable to determine much information from rose diagrams alone; as in previous studies (Savage

Figure 5.5: Stacked data from raw data from Figure 5.3. Pattern of arrivals are conserved after the stacking processes. The incoming shear-wave (red-dashed line) is now flattened because the traces were trimmed around it. Dashed lines are as indicated in Figure 5.3.

et al., 2016; Evanzia et al., 2017) it is necessary to examine the average fast azimuths.

Figure 5.6: Example of splitting results from MFAST of stack 123 on the SAHKE II array. Top label is measurement ID. (a) Bandpass filtered (0.2-3Hz) East (e), North (n), and vertical (z) waveforms. Solid line is the shear-wave arrival. Dashed lines are minimum (1) start and maximum (4) end times for windows used in processing. Grey window is the window chosen as the best measurement. (b) Rotated waveforms into incoming polarization direction (p) and its perpendicular (p+), for original filtered (top) and the waveforms corrected for delay time (bottom). Dashed lines are the maximum (2) start and minimum (3) end times for other measurement windows. Dashed lines 1 and 4 and grey window are as they were in (a). Solid line (red) is the shear-wave arrival. (c) Fast direction azimuth and delay time for each window as a function of window number. X marks the chosen fast direction/delay time and window. (d) Clusters of five or more measurements as a function of fast direction and delay time. X marks the chosen final cluster. (e) Original (left) and corrected (right) waveform (top) and particle motion (bottom) for the final window (grey). (f), similar to (d), but include contours of the smallest eigenvalues of the covariance matrix for the final measurement (X). Bottom label gives final grade, fast direction azimuth, and delay time, including errors for splitting measurement.

West of the Wairarapa fault the average fast azimuths generally trend between NNW-SSE and NNE-SSW, where as east of the Wairarapa fault there is more variation, but the trend is typically NW-SE and N-S east of the Dry Creek fault (Figure 5.9). The variation in the average fast azimuth calculated in this study, is sub-parallel to parallel with averages made by Evanzia et al. (2017) on stations in the SAHKE I network, which lie in close proximity to the SAHKE II array (Figure 5.9). After combining and calculating the mean of four subregions (1: West of the Wellington fault [green]; 2: between the Wellington and Wairarapa faults [tan]; 3: inside the Wairarapa basin [red]; 4: East of the Wairarapa basin [blue]) of fast azimuths, there is clear variation west and east of the Wairarapa fault (Figure 5.9, Table 5.1). The average fast azimuths west of the Wellington fault and between the Wellington and Wairarapa faults are N-S ($18^\circ \pm 12$) and NNE-SSW ($65^\circ \pm 12$), respectively, whereas the average fast azimuth in the Wairarapa basin and east of the Wairarapa basin are both NNW-SSE, $-37^\circ \pm 11$ and $08^\circ \pm 10$, respectively (Figure 5.9).

In order to assess the validity of the stacking methods implemented in this study we take a sample of the unstacked seismic traces of two regions (west of the Wellington fault and in the Wairarapa basin) and rotate them into the fast azimuth (Table 5.1) and a perpendicular azimuth (fast azimuth + 90°) (Figure 5.10, red and blue respectively). Some traces west of the Wellington fault and from within the Wairarapa basin show earlier arrivals for those traces rotated into the fast azimuth (Figure 5.10). Variable

Event: 2011-05-09_11-11-36 Stack: 123 Filter: 0.2-3.0 hz

Grade: ACI

Fast Azimuth: 30.0 +/- 8.5

Delay Time: 0.068 +/- 0.007

Figure 5.7: Density plots comparing various attributes of all A and B splitting measurements made using MFAST and filters used in splitting. Measurement attributes compared are: angle of incidence, back azimuth, delay time, distance (earthquake - station), and fast direction azimuth. Hotter colors (reds) indicated a higher occurrence. Lower frequency (0.2 - 5 Hz) filters gave more high quality (A and B quality) measurements. No one attribute is dependent on any other, indicating a singular source for the anisotropy measurements calculated.

Figure 5.8: Fast azimuth (degrees from North) measurements from all stacked traces as a function of distance along the SAHKE II array. Distance 0 km indicates location of westernmost seismic station. Black dot are fast azimuth measurements. Oranges, yellows and greens indicate increase density of measurements. Red-line is the 20-point moving average. Dashed-grey lines separate difference regions of interest (from West-East, see Figure 5.1 and 5.8): West-coast to the Wellington fault, Wellington fault to the Wairarapa fault, the Wairarapa Basin, and Dry Creek fault to East-coast. Solid-white lines mark the average fast azimuth and dashed-white lines show the 95% confidence intervals.

Region	Stations	# of Stacks	Fast Az.	95% CI	Delay Time	95% CI
West of Well.	55	001-029	18°	±12	0.144 s	± 0.027
Well. - Wair.	89	030-070	65°	±12	0.181 s	± 0.027
Wair. - DC.	67	071-103	-37°	±11	0.173 s	± 0.029
East of DC.	80	104-142	08°	±10	0.189 s	± 0.026
All Regions	291	001-142	21.56°	±06	0.175 s	± 0.014
<i>West</i>	17	N/A	66°	±18	0.132 s	± 0.016
<i>Basin</i>	17	N/A	-43°	±35	0.167 s	± 0.025
<i>East</i>	16	N/A	74°	±11	0.165 s	± 0.028

Table 5.1: Averaging fast direction across SAHKE II array. Averaging over four groups of stacks: (1) west of the Wellington fault; (2) between the Wellington and Wairarapa fault; (3) in the Wairarapa Basin; (4) east of the Dry Creek fault. Italicized regions (West, Basin, East) indicate measurements made by Evanzia et al. (2017). Column 1 identifies the region, column 2 identifies the number of stations in that region, column 3 identifies the number of stacks in the region, columns 4 and 5 give the average fast azimuth and 95% confidence interval, and columns 6 and 7 give the average delay time and 95% confidence interval.

delay times between even closely spaced traces indicate that the fast azimuth and delay time can change rapidly.

5.8 Discussion

The lack of a strong relationship between the splitting parameters (Figure 5.7) and given that averages using all data, data from the four closest earthquake, data from five random, and data from a single earthquake (Appendix C Figure S1–S20) yield similar results implies a similar local source for the measured anisotropy and shows the stacked measurements are not heavily dominated by a single earthquake. It is unlikely that the majority of the observed local source of anisotropy is the result of larger regional structural fabrics (i.e., aligned rock fabric, fault structures, and sedimentary bedding plains) because there are no known pervasive metamorphic or finely-well-bedded sedimentary terranes across the southern North Island. Based on the finding from Savage et al. (2007) of dipping beds of blueschist in the westernmost southern North Island, if this feature continued north, then it could account for some of the scatter we observe at the westernmost stations.

The measured splitting is not from a pervasive anisotropy along the whole wave path because the delay times do not vary with station-event distance or depth (Figure 5.7), which suggests it is probably the result of a near surface feature. Assuming the anisotropy is limited to the crust (15 ± 5 km or above) (Evanzia et al., 2017), an average shear-wave velocity of 3.5 km/s (Eberhart-Phillips et al., 2010), and an average delay time of 0.175 ± 0.014 s, we estimate the strength of anisotropy to be $4.2 \pm 0.5\%$, which

Figure 5.9: Circular-mean fast azimuth for each stack. Colors (e.g., green, tan, red, blue) indicate grouping of mean azimuths for averaging. Colored numbers and yellow wedges indicate the average fast direction azimuth and 95% confidence interval for groups over which they lie.

agrees well with previous estimations done by Gledhill and Stuart (1996); Evanzia et al. (2017), who calculated anisotropy strength of 4% and $3.7 \pm 1.2\%$, respectively, in the southern North Island. Crampin (1994) noted that with anisotropy from micro-cracks within the crust tend to result in 1.5% to 4.5% strength in anisotropy, which is similar to the $4.2 \pm 0.5\%$ found in this study.

5.8.1 West of Wairarapa Fault

West of the Wairarapa fault the fast azimuths generally trend between NNW-SSE and NNE-SSW (Figure 5.8 and 5.9). West of the Wellington fault where the average fast azimuth is NNE-SSW ($18^\circ \pm 12^\circ$) and the major fault structures strike NE-SW (Van Dissen and Berryman, 1996) (Figure 5.11). Between the Wairarapa and Wellington fault, we observe a rotation of the average fast azimuth trending NE-SW ($65^\circ \pm 12^\circ$), which is coeval with a change rotation in strike of the Wellington fault from NNE-SSW to NE-SW (Figure 5.11). There is no clear relationship between various splitting parameters

(Figure 5.7), but there is a clear alignment of the fast azimuth to the prevailing NW-SE trending faults. Therefore, the fast azimuth west of the Wairarapa fault is likely the result of near-surface structural sources (i.e., faults). It is possible that the scatter we observed is due to the opening and closing of cracks parallel and perpendicular to the fast azimuth (i.e., SHmax) (Crampin, 1994).

The average fast azimuth of $65^\circ \pm 12$ observed between the Wellington and Wairarapa faults in this study, is similar to the average fast azimuth of $66^\circ \pm 18$ observed in west of the Wairarapa fault by Evanzia et al. (2017). However, west of the Wellington fault, the average fast azimuth of $18^\circ \pm 12$ found in this study differs significantly from the more regional Evanzia et al. (2017) fast azimuth observations. This would suggest that the fast azimuth of $18^\circ \pm$ observed west of the Wellington fault, is a more localized feature, or that measurements from stations between the Wellington and Wairarapa faults dominated the average fast azimuth west of the Wairarapa fault in the Evanzia et al. (2017) study.

5.8.2 East of Wairarapa Fault

East of the Wairarapa fault there is a clear change in the trend of the average fast azimuth. In the Wairarapa basin the average fast azimuth trends NNW-SSW ($-37^\circ \pm 11$), which is oblique, nearly perpendicular, to the orientation of the major local fault system (Figure 5.8, 5.9, and 5.11). The average fast azimuth of $-37^\circ \pm 11$ observed across the Wairarapa basin, is similar to those observed by Evanzia et al. (2017), who calculated an average fast azimuth of $-44^\circ \pm 35$ throughout the Wairarapa basin. This fast azimuth and the NW-SE orientation of the major faults would suggest a non-structural origin for the fast azimuth, unlike west of the Wairarapa fault. The rotation of the fast azimuth is likely due to the rotation of sigma one (maximum compressive stress direction) or a drop in amplitude of sigma one relative to sigma two (median compressive stress direction) and three (minimum compressive stress direction). On a regional scale, Evanzia et al. (2017) identified this rotation and attributed it to an increased contribution to the stress field by gravitational and tectonic loading stresses.

East of the Dry Creek fault, the average fast direction is NNW-SSE ($08^\circ \pm 10$). The average fast azimuth of $08^\circ \pm 10$ east of the Dry Creek fault is significantly different than the regional average of $74^\circ \pm 11$, calculated by Evanzia et al. (2017). This may be due to the larger area that Evanzia et al. (2017) averaged the fast azimuth over. As shown in Figure 3 of Evanzia et al. (2017) average fast azimuths differ significantly in the northern and southern East region. Similar to west of the Wellington fault, this difference suggests the average fast azimuth observed in this study result from localized features that are not pervasive throughout the region. Figure 5.11 shows that the fast azimuth east of the Dry Creek fault is similar in orientation to faults in the easternmost southern North Island. It is possible that some of the splitting in this area is the result of unknown near surface fault structures. The differences in the average fast azimuth

Figure 5.10: The result of rotating a sample of the raw (no-offset) unstacked seismic traces into the fast azimuth (red) and its perpendicular (blue) calculated using MFAST. Right: Region 1 (West of the Wellington fault); Left: Region 3: (the Wairarapa Basin). Overall the traces rotated in the fast azimuth orientation arrive slightly earlier than those rotated perpendicular to that orientation. Not all traces show the same amount of time difference; this is to be expected because the fast azimuth orientation is an average, and that the fast azimuth changes rapidly across the SAHKE II line. Additionally, some pairs of rotated traces are similar, others are not, showing the presence of scattering.

Figure 5.11: Average fast azimuth along the SAHKE II array. West of the Wairarapa fault the fast azimuth orientation is similar to the strike of the local faults. In the Wairarapa basin, the fast azimuth is oblique of the strike of the local faults.

observed in this and the Evanzia et al. (2017) study demonstrates that either variation in rotation of the principal stress axes (sigma one, two, and three) from contributions to the stress field by gravitational and tectonic loading stresses are not consistent or that the fast azimuth observed in this study results from something more localized such as small fault structures.

5.9 Conclusions

Making use of 21 local earthquakes and 291 stations, we evaluated seismic anisotropy across the southern North Island, New Zealand (Figure 5.1). To bolster the SNR we stacked five adjacent stations (Figure 5.4), with a sliding window overlapping three stations, totaling 142 stacked stations. As shown in Figure 5.7, the lack of splitting parameters dependence allowed us to average all available splitting measurements. We calculated an average delay time of 0.175 s and estimated the strength of anisotropy

to be $4.2 \pm 0.5\%$, which is on par with Gledhill and Stuart (1996) 4% and Evanzia et al. (2017) $3.7 \pm 1.2\%$. West of the Wellington fault we attributed the anisotropy and resulting fast azimuths to structure-controlled sources in the upper 15 km of the Australian plate (Figure 5.11). Between the Wairarapa and Wellington faults the anisotropy is structures-controlled by the major NW-SE striking faults (Figure 5.11). East of the Wairarapa fault, the fast azimuth results suggest a non-structural stress-controlled seismic anisotropy, and is reflective of the SHmax orientation.

This study shows that passive and active source seismic experiments do not have to be mutually exclusive, in terms of data collection or analysis method. Given the right experimental parameters, passive and active source methodology can be interchangeable. It would be advantageous for experimenters to have to not be beholden to single seismic experiment paradigm when carrying out in large seismic experiments.

5.10 Acknowledgements

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Chapter 6

Preliminary Examination of Long-Term and Short-Term Strain Rates in Central New Zealand

6.1 Abstract

We determine strain parameters (i.e., shear strain rate, dilatation, vorticity) from the southern North Island to the northern South Island, New Zealand, using continuous Global Positioning System (cGPS) data. This study makes use of daily position solutions calculated by GeoNet to generate three station-velocity datasets: (1) Long-term; (2) Inter-Slow-Slip Event (Inter-SSE); (3) Co-seismic movement during the 2016 $M_W 7.8$ Kaikōura earthquake. Long-term station velocities showed high shear strain rates in the Wairarapa and Cook Strait regions, overall compressional dilatation, and overall positive (clockwise) vorticity. Inter-SSE station velocities showed elevated shear strain rates in the Cook Strait region, overall compressional dilatation, and overall positive (clockwise) vorticity. Co-seismic station velocities resulted in extremely high shear strain rates in the Kaikōura region of the South Island, predominant compressional dilatation, and positive (clockwise) vorticity in North Island and negative (counter-clockwise) vorticity in South Island. Preliminary dislocation modeling shows locking to be above ~ 20 km depth, and that SSEs have accommodated $\sim 65\%$ of slip in their locations below the southern North Island during the observed cGPS epochs. Strain parameters calculated using long-term station velocities are applicable to long-term forecasting of seismic hazards, whereas strain parameters calculated from inter-SSE strain parameters would be more suitable for short-term seismic hazard forecasting (e.g., aftershock hazard assessment) in the southern North Island and northern South Island.

6.2 Introduction

In 2015 there were > 8000 earthquakes ($M > 1$) in southern North Island and northern South Island (<https://quakesearch.geonet.org.nz/>). The sources of the numerous earthquakes are the southern Hikurangi subduction zone and the NE-SW transpressional crustal faults in the Australian plate above. The presence and seismically active nature of these tectonic features highlight the need to characterize them in order to mitigate the hazards they represent. Observations of strain can aid in the understanding of seismic hazards by characterizing seismic deformation associated with the southern Hikurangi subduction zone and the numerous surface faults in the southern North and northern South Island. The installation of a dense continuous Global Positioning System (cGPS) network (Figure 6.1) has facilitated an in-depth study of strain rates in central New Zealand. Controls on strain rates in North Island are greater than in South Island, due to the cGPS network station distribution (~ 20 km and ~ 100 km station spacing, respectively).

6.2.1 Tectonic Setting

In the vicinity of central New Zealand, the contemporary Pacific-Australian plate boundary consists of the oblique subduction of the Pacific plate under the Australian plate at ~ 38 mm/yr (Figure 6.1) (Beavan and Haines, 2001; Beavan et al., 2002). Slip along the Hikurangi margin is not uniform (Walcott, 1984). Wallace et al. (2004, 2009, 2012) showed there to be a slip deficit of 20 - 30 mm/yr on the plate interface below the southern North Island. The presence of a slip deficit is an indication that the overriding Australian plate is 'partially locked' or 'coupled' to the subducting Pacific plate. Down-dip of the coupled region on the plate interface, slow-slip events (SSEs) occur approximately every six years on the plate interface, lasting weeks to months, at depths of ~ 30 to 60 km (Wallace and Beavan, 2010; Lamb and Smith, 2013; Wallace et al., 2014). Coupling of the plate interface could result in transfer of stress to the Australian plate, leading to more and larger overriding plate earthquakes and/or could result in a large stress release via mega-thrust subduction earthquake. The stress analysis of Evanzia et al. (2017) (see Chapter 3) indicates that stress transfer between the overriding and subducting plates is mainly occurring in the western region of southern North Island. Wallace et al. (2009) estimated that the southern Hikurangi margin coupled section is theoretically capable of producing a $M_W 8.2$ to $M_W 8.7$ earthquake.

Crustal faults in southern North Island and northern South Island consist of NE-SW trending dextral transpressional faults (Figure 6.1, New Zealand active fault database, www.gns.cri.nz). 60 to 90% of margin-parallel motion is accommodated by major onshore faults such as the Wellington and Wairarapa faults (Langridge et al., 2005), whereas it has been proposed by Wallace et al. (2009) that margin-perpendicular motion is accommodated on the subduction thrust by episodic slip on scale of 100s to

Figure 6.1: Tectonics of the North Island and Northern South Island. Location of continuous global positioning system (cGPS) stations (green circles). Regions of slip during slow-slip events (SSEs) are indicated by brown lines. Red-star shows epicenter location of $M_W 7.8$ Kaikōura earthquake (Kaiser et al., 2017). Dashed-black lines show plate interface depth (Williams et al., 2013). Thick-black lines show plate boundaries (Coffin et al., 1998) and grey lines show active faults (<https://data.gns.cri.nz/af/>). Map-inset: New Zealand tectonics showing location of plate boundaries (black lines): Alpine Fault and Hikurangi Margin (HK), in relative relation to Australian plate (AU) and Pacific plate (PA) (Coffin et al., 1998).

1000s of years.

6.2.2 Previous GPS Studies

In the previous four decades there have been numerous geodetic studies examining tectonic movement, strain rates, slow-slip events (SSEs), and plate coupling at the southern Hikurangi margin (e.g., Walcott, 1978, 1984; Lamb and Vella, 1987; Darby and Beavan, 2001; Wallace et al., 2004, 2009, 2012; Lamb and Smith, 2013; Lamb, 2015; Beavan et al., 2016). Walcott (1978), Lamb and Vella (1987), and Beanland and Haines (1998) demonstrated that the region east of the Wairarapa fault is dominated by compression (i.e., shortening rate $>$ shear rate), whereas the region west of the Wairarapa fault is dominated by dextral shear deformation (i.e., shortening rate $<$ shear rate). Lamb (2015), using a smoothed velocity field calculated from decadal cGPS strain parameters, showed a zone of high dextral strain rate from the central South Island up into the eastern region of the North Island, with extension in the central North Island, and compression elsewhere.

The largest earthquake in New Zealand since 1855 occurred in late 2016 and was located in the eastern region of the northern South Island (Figure 6.1). The 2016 $M_W 7.8$ Kaikōura earthquake resulted in tsunamis, tens of thousands of landslides, and infrastructural damage (Kaiser et al., 2017). The complex rupture involved at least 15 separate faults extending 150 km from northern Canterbury to the Cook Strait (Hamling et al., 2017; Cesca et al., 2017). The earthquake ruptured with oblique right-lateral thrust motion (Kaiser et al., 2017; Zheng et al., 2017). A maximum surface displacement of 10-12 m (predominantly dextral) was observed on the Kekerengu fault (Van Dissen and Little, 2017). Coulomb modeling of the Kaikōura earthquake indicated that the southern extents of the Awatere and Clarence faults in the South Island are in regions of increased stress, and that the Ohariu, Wellington, and Wairarapa faults, in the southern North Island, have been brought closer to failure (Xu et al., 2018). Wallace et al. (2017) observed SSEs west of the southern North Island and along the east coast of the North Island in the days following the Kaikōura earthquake. These triggered SSEs demonstrate that the Kaikōura earthquake affected slip along the Hikurangi plate interface.

This study expands upon previous cGPS strain studies (Wallace and Beavan, 2010; Lamb and Smith, 2013) by assessing strain parameters using two station velocity datasets that are referred to as (1) long-term and (2) inter-SSE (short-term). The utilization of the various datasets allows for the characterization of the effects of SSEs on strain parameters. This study provides new strain parameters for consideration when assessing long-term and short-term seismic hazards in the southern North Island and northern South Island of New Zealand. Additionally we present observations of strain parameters resulting from co-seismic movement from the 2016 Kaikōura earthquake.

Figure 6.2: Example of longterm displacement (mm) measure at the cGPS station (KAPT) located on Kapiti Island, off the east coast of the southern North Island (Figure 6.1). Kapiti slow-slip events (SSEs) are clearly discernible as deviations from the predominantly linear displacement pattern.

6.3 Methodology

6.3.1 cGPS Station Velocities

cGPS station velocities are derived by calculating the daily average displacement over time for both the eastern and northern components. The long-term cGPS station velocity dataset is determined by a linear best-fit for the daily solutions over the entire operational duration of the cGPS site (years to decades, pre-2016 Kaikōura earthquake), if no earthquakes were present in the data. The inter-SSE station velocity dataset is calculated by the linear best-fit of only inter-SSE time periods. Non-SSE time periods were determined visually on a station by station basis, as individual stations are affected in different ways by SSEs. Examples of removed SSEs are the Kapiti 2003, Manawatu 2004-2005, Southern Hawke's Bay 2006, and the Kapiti 2008 events (Wallace and Beavan, 2010). The clear instances of displacement due to earthquakes (e.g. 2013 Seddon earthquake) were removed for both datasets. The co-seismic Kaikōura dataset is calculated by measuring offset between the day before the Kaikōura earthquake and four days after. A period of four days was used in order to capture enough data points to make reasonably good measurement of offset.

For the purposes of dislocation modeling, the long-term and inter-SSE datasets are transformed from the International Terrestrial Reference Frame (ITRF2008) (Altamimi et al., 2012) to an Australian plate Reference Frame (AURF), using the methods outlined in Chapter 2 (*Methods: Reference Frame Transformation*). Dislocation theory was first described by Steketee (1958); this study uses the methods outlined in Okada (1985, 1992) and Lamb and Smith (2013) to model changes in surface displacement due to

Figure 6.3: Example of inter slow-slip event (interSSE) displacement (mm) measure at the cGPS station (KAPT) located on Kapiti Island, off the east coast of the southern North Island (Figure 6.1. Inter-SSE time periods measured on linear segments of cGPS displacement.

Figure 6.4: The Delaunay network shows the triangular region that the strain parameters were calculated within, for the long-term and inter-SSE datasets. Red location markers refer to areas of interesting in subsequent sections. Thick black and grey lines are as indicated in Figure 6.1.

varying amounts of slip along the subduction plate interface. It was necessary to transform the cGPS velocities from an ITRF2008 reference frame to a AUS reference frame, because the method requires one block of the dislocation model to be stable. In the simple models used in this study the 'locking point' identifies the boundary between slip and no slip on the plate interface. The dislocation modeling done in this study expands on the work done by Lamb and Smith (2013), by taking advantage of the longer time period now available for cGPS measurements (2000 - 2016 pre-Kaikōura earthquake), allowing an improved understanding of the effects of SSEs.

6.3.2 Shear Strain Rate, Dilatation, Vorticity

Shear strain rate, dilatation, and vorticity are calculated using the Lamb (2000, 2015) method. Strain parameters are calculated from the spatial derivatives of the velocities and are then modeled as a continuous function in a triangular (Delauney) network (Figure 6.4). Strain rates are derived as spatial derivatives of velocities u, v parallel to x, y axes respectively:

$$\dot{\gamma}_1 = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}; \quad \dot{\gamma}_2 = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \quad (6.1)$$

$$\dot{\Gamma} = \sqrt{\dot{\gamma}_1^2 + \dot{\gamma}_2^2} \quad (6.2)$$

$$\dot{\omega} = \frac{1}{2} \left(\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} \right); \quad \dot{\Delta} = \frac{1}{2} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \quad (6.3)$$

Shear strain rate ($\dot{\Gamma}$: $\dot{\gamma}_1$ and $\dot{\gamma}_2$) describes the rate of horizontal shape change, vertical vorticity ($\dot{\omega}$) defines the rotation of a rigid body, and dilatation ($\dot{\Delta}$) describes the expansion and contraction, per unit area, of a horizontal area.

6.4 Results

6.4.1 cGPS Station Velocities

cGPS station velocities are most affected when located above or in proximity to the SSEs (Figure 6.4 and 6.5). The cGPS long-term velocities of sites located nearest to Wellington, in the southern North Island, were affected little by SSEs. This may be due to the long duration of the cGPS site (2000 - present), indicating that the SSEs are effectively averaged out. Long-term station velocities trend more northward than inter-SSE station velocities, as a result of the occurrence of SSEs (Figure 6.5). This is due to the eastward and up-dip slip direction of the SSEs (Wallace et al., 2009; Wallace and Beavan, 2010). There is little to no evidence of SSEs at stations in Nelson, Kaikōura, and West Coast of the South Island and stations located in the Wairarapa region of North Island (Figure 6.4 and 6.5).

Figure 6.5: cGPS velocities calculated from daily-solutions excluding SSEs (inter-SSE, magenta) and velocities calculated including SSEs (long-Term, blue) in the ITRF2008 reference frame. Thick black, grey, and brown lines are as indicated in Figure 6.1.

After transformation of velocities into the Australian Plate Reference Frame (Lamb and Smith, 2013) the cGPS velocities generally trend in the Pacific-Australian plate convergence direction. Similar variations in station velocities can be seen due to SSEs (Figure 6.6).

6.4.2 Long-Term Strain Rate Parameters

Long-Term Shear Strain Rate

The highest shear strain rates (2 to 3×10^{-7} /yr) are observed in the Marlborough region of South Island, the Wellington region of North Island, and the Cook Strait region (Figure 6.8). The shear strain rates are lower in the Wairarapa region of the southern North Island. This coincides with regional faulting patterns (www.gns.cri.nz), which show relatively little faulting in the Wairarapa region. The low shear strain rates (0 to 1×10^{-7} /yr) in the Wairarapa also corresponds to the higher plate interface coupling in the Wairarapa region of the southern North Island (Wallace et al., 2004, 2009, 2012). The shear strain rates observed in this study are larger than those calculated by Beavan and Haines (2001) ($\sim 0.25 \times 10^{-7}$ /yr) using campaign GPS, but are similar to those calculated by Lamb (2015) ($\sim 2 \times 10^{-7}$ /yr) using a combination of cGPS and

Figure 6.6: cGPS velocities calculated from daily-solutions excluding SSEs (inter-SSE, magenta) and calculated including SSEs (long-term, blue) in an Australian plate reference frame. Thick black, grey, and brown lines are as indicated in Figure 6.1.

campaign GPS data.

Long-Term Dilation

There is little variation in dilation throughout southern North Island and northern South Islands, with compression (red: -1.5 to $0 \times 10^{-7}/\text{yr}$) dominating most of the region (Figure 6.8). The compressional dilation rates observed here are again larger than those calculated by Beavan and Haines (2001) ($.15 \times 10^{-7}/\text{yr}$), but are again similar to Lamb (2015) (-1.5 to $-0.5 \times 10^{-7}/\text{yr}$). This is expected, given the prevalence of transpressional faulting and the proximity of the study area to the subduction trench. The expansion (blue) in the Manawatu region of the North Island and Marlborough region of the South Island (Figure 6.8) are possibly artifacts due to short station operating durations or edge effects. Short operating durations of cGPS sites result in the inclusion of only one or two SSEs, which would highly skew a station's velocity. This could be clearly seen in the Kapiti cGPS station record (Figure 6.2) if the record only contain daily solutions from day 2500 to day 4250. This duration would result in an average displacement over time that would be much more skew to a eastward direction (i.e., a less negative slop).

Long-Term Vorticity

The entirety of the study region is undergoing positive (clockwise) rotation (1 to $3^\circ \times 10^{-7}/\text{yr}$) (Figure 6.8). Regions of increased positive rotation are co-located with increased shear strain rates in the southern North Island. Similar amounts of clockwise rotation have been observed previously by Wallace et al. (2004) (0.5 to $3.8^\circ \times 10^{-7}/\text{yr}$) and Lamb (2015) ($\sim 2^\circ \times 10^{-7}/\text{yr}$).

6.4.3 Inter-SSE (Short-Term) Strain Rate Parameters

Inter-SSE Shear Strain Rate

Overall the North Island exhibits a lower inter-SSE shear strain rate than that of the South Island (0 to $1 \times 10^{-7}/\text{yr}$ and 1 to $2 \times 10^{-7}/\text{yr}$, respectively) (Figure 6.9). The highest shear strain rates ($2 \times 10^{-7}/\text{yr}$) are observed between the Cook Strait region and the North and South Islands. Unlike the long-term shear strain rates, the inter-SSE shear strain rates are similar to those calculated by Beavan and Haines (2001) ($\sim .25 \times 10^{-7}/\text{yr}$). This may indicate that the campaign GPS datum from the southern North Island used by Beavan and Haines (2001) was collected during an inter-SSE time period. The large regions of high shear strain rate associated with the Manawatu region in North Island could be related to the tectonics of Taupo Volcanic Zone (TVZ).

Inter-SSE Dilatation

As was seen in the long-term dilation (Figure 6.8), the study area is predominantly under compression (Figure 6.9). There are several small areas of expansion in the Marlborough region of the northern South Island and the Manawatu region of the North Island (Figure 6.9). The small area of expansion in the Manawatu region is likely the southern continuation of the TVZ. The lower inter-SSE compressional dilatation rates ($\sim .75$ to $0 \times 10^{-7}/\text{yr}$) are similar to those calculated by Beavan and Haines (2001) (1.5 to $0 \times 10^{-7}/\text{yr}$).

Inter-SSE Vorticity

As seen in Wallace et al. (2004), Lamb (2015), and the previously calculated vorticity (Figure 6.8), the entire study area is rotating positively (clockwise) (Figure 6.9). The magnitude of rotation calculated using inter-SSE station velocities are less than those calculated with long-term station velocities (1 to $2^\circ \times 10^{-7}/\text{yr}$ and 1 to $3^\circ \times 10^{-7}/\text{yr}$, respectively).

6.4.4 Co-Seismic 2016 Kaikōura Earthquake

cGPS stations in the vicinity of the 2016 Kaikōura earthquake are very limited (Figure 6.7). As a result, the associated strain rate parameters are extrapolated over distances of several 10s of kms.

Co-Seismic Shear Strain Rate

Co-seismic shear strain rates are greatest nearest the epicenter of the Kaikōura earthquake extending north along the east coast of the northern South Island, mimicking the rupture propagation direction (Litchfield et al., 2016; Bradley et al., 2017) (Figure 6.7 and 6.10). The area of high shear strain rate encompasses a large majority of the recorded aftershocks located north of and along the east coast (see Figure 4 in Cesca et al., 2017) of the northern South Island.

Co-Seismic Dilatation

There are several distinct regions of expansion (blue) and compression (red) resulting from the Kaikōura earthquake. There is compression in northern South Island and the western half of North Island (Figure 6.10). Compressional axes mimic the shear strain rate pattern, radiating out in a semi-circular manner from the northwest coast of the South Island (Figure 6.10). Extension is observed along the entirety of the east coast of the North Island and the West Coast region of the South Island. Extensional axes along the east coast of the North Island show that extension is oriented E-W (Figure 6.10).

Co-Seismic Vorticity

The southern North Island responded to the Kaikōura earthquake by rotating in a positive direction (clockwise), while the northern South Island rotated in a negative (counter clockwise) direction (Figure 6.10). Some regions of negative rotation are present in the north of the study area.

Figure 6.7: cGPS velocities calculated from offset due to 2016 $M_W 7.8$ Kiakoura earthquake in ITRF2008 reference frame. Velocities determined via offset between 13th - 17th of November 2016. As expected the velocities (black-arrows) of those stations closest in proximity to the hypocenter are most greatly affected. Red star is epicenter of 2016 $M_W 7.8$ Kiakoura earthquake and red lines are ruptured faults (Kaiser et al., 2017; Cesca et al., 2017). Grey lines indicate active faults (<https://data.gns.cri.nz/af/>).

Figure 6.8: A map of smoothed (Gaussian filter of 100 km) long-term strain parameters (shear strain rate, dilatation, vorticity) calculated from station velocities pre $M_w 7.8$ KaiKoura 2016 earthquake. Black triangulated regions shows Delaunay network. Grey lines indicate active faults (<https://data.gns.cri.nz/af/>).

Figure 6.9: Map of smoothed (Gaussian filter of 100 km) shear strain rate, dilatation, and vorticity calculated from inter-SSE station velocities. In general, the strain parameters are more uniform and show lower magnitudes compared to those calculated using long-term station velocities. Black triangulated regions shows Delaunay network. Grey lines indicate active faults (<https://data.gns.cri.nz/af/>).

Figure 6.10: The co-seismic strain parameters calculated for the $M_W 7.8$ Kaikōura earthquake were calculated in the same manner as the previous strain parameters. The Delaunay network (black triangular regions) used for the co-seismic strain parameters does not calculate strain parameters in triangular regions that cross over faults that were displaced. Grey lines indicate active faults (<https://data.gns.cri.nz/af/>).

6.5 Discussion

6.5.1 Comparing Strain Parameters

The variation in strain rate parameters is illustrated with a series of ± 10 km swath profiles across the four regions of central New Zealand: (1) Manawatu North Island (Figure 6.11), (2) Southern North Island (Figure 6.12), (3) Cook Strait (Figure 6.13), and (4) Northern South Island (Figure 6.14).

Manawatu North Island

Overall, there is no major differences between long-term and inter-SSE strain parameters in the Manawatu region of the North Island (Figure 6.11). In general, strain parameters calculated from inter-SSE velocities are more dispersive than those calculated using long-term velocities. The increase in shear strain rate and vorticity, and the variation in dilatation on the eastern end of the cross-section are probably the result of the long-term effects of SSEs in the Southern Hawke's Bay and the Manawatu regions (Wallace and Beavan, 2010).

Southern North Island

Long-term and inter-SSE strain parameters show similar patterns, but differ in magnitude, in the southern North Island (Figure 6.12). Shear strain rate and vorticity calculated from long-term velocities show an increased magnitude (2 to $3 \times 10^{-7}/\text{yr}$, $\sim 3^\circ \times 10^{-7}/\text{yr}$) off the west coast of the southern North Island to the Wairarapa region (~ 75 km to ~ 175 km, see Figure 6.12). The differences in strain parameters can be attributed to the long-term effects of the Kapiti SSEs (Wallace and Beavan, 2010), which are located just south of the cross-section off the west coast of the southern North Island (Figure 6.1).

Cook Strait

Figure 6.13 shows the largest variations in strain parameter magnitudes. Elevated strain parameter magnitudes (shear strain rate: $\sim 3 \times 10^{-7}/\text{yr}$, vorticity: $\sim 3^\circ \times 10^{-7}/\text{yr}$, dilatation: $0.5 \times 10^{-7}/\text{yr}$) calculated in the Cook Strait from both datasets span greater distances (~ 40 km to ~ 150 km) than those calculated in the other regions (compare Figure 6.12, 6.13, and 6.14). The longer wavelength features in Figure 6.13 are likely artifacts related to the increased size of the triangular regions that the strain parameters are calculated within (Figure 6.4). There is a noticeable increase in magnitude of all long-term strain parameters, compared to inter-SSE strain parameters (Figure 6.13). The increase in magnitude can be attributed to the long-term effects of Kapiti SSEs (Wallace and Beavan, 2010).

Northern South Island

Figure 6.14 shows there is little to no difference between long-term and inter-SSE strain parameters. This is expected as there is no record of SSEs in this region (Figure 6.1) (Wallace et al., 2004; Wallace and Beavan, 2010).

6.5.2 Co-Seismic Strain Rates of 2016 Kaikōura Earthquake

The limited extent of the high shear strain rate and the rotations of North Island and South Islands as distinct blocks (Figure 6.10) may indicate why aftershocks were predominantly restricted to near by and cos-seismically ruptured faults at northeastern coast of South Island and the Cook Strait region (see Figure 4 in Cesca et al., 2017). Though principally compressional, the dilatation response to the Kaikōura earthquake was extensional in the eastern half of the North Island (Figure 6.10). It is possible that the extension observed in the eastern half of the North Island is the result of triggered SSEs (Wallace et al., 2017). The extension may have resulted in the accommodation of some of the stress that has built-up in this region due to the coupled nature of the plate interface (Wallace and Beavan, 2010). Based on these preliminary results it is unclear over what time period this extension persisted and how much, if any, stress has been accommodated.

6.5.3 Preliminary Analysis Mega-thrust Locking Depths

The strain rate data can be modeled in terms of slip on the underlying subduction mega-thrust with a simplistic elastic dislocation model.

Based on the higher density of the cGPS network (Figure 6.1), the prevalence of previous studies (e.g., Lamb and Smith, 2013; Henrys et al., 2013), and the location of the coupled plate interface (Wallace et al., 2004, 2009, 2012), preliminary dislocation modeling was performed (in AUS reference frame) along a profile across the southern North Island (cross-section shown in Figure 6.12). Here, the location of the fully locked versus freely slipping sections of the subduction mega-thrust and the influence of SSEs are expressed in terms of an effective coupling factor of either 0 and 1 (e.g. Lamb and Smith (2013)).

Model 1 (long-term velocities, Figure 6.15) gives a locking point depth of ~ 21 km on the plate interface. This depth is between the locking points calculated by Lamb and Smith (2013), 15 km in the central North Island to 35 km in the northern South Island and Darby and Beavan (2001), who found maximum coupling ranged from 16 km to 24 km, in the southern North Island.

Figure 6.11: Comparing cross-section (red-dashed line), spanning the south-central North Island of shear strain rate, dilatation, and vorticity, for the inter-SSE (short-term) and long-term datasets. Red-dashed line shows cross section. Grey lines indicate active faults (<https://data.gns.cri.nz/af/>).

Figure 6.12: Comparing cross-section (red-dashed line), spanning the southern North Island of shear strain rate, dilatation, and vorticity, for the inter-SSE (short-term) and long-term datasets. Red-dashed line shows cross section. Grey lines indicate active faults (<https://data.gns.cri.nz/af/>).

Figure 6.13: Comparing cross-section (red-dashed line), spanning the Cook Straits (between the North and South Island) of shear strain rate, dilatation, and vorticity, for the inter-SSE (short-term) and long-term datasets. Red-dashed line shows cross section. Grey lines indicate active faults (<https://data.gns.cri.nz/af/>).

Figure 6.14: Comparing cross-section (red-dashed line) spanning the northern South Island, of shear strain rate, dilatation, and vorticity, for the inter-SSE (short-term) and long-term datasets. Red-dashed line shows cross section. Grey lines indicate active faults (<https://data.gns.cri.nz/af/>).

Figure 6.15: Dislocation modeling results calculated using station velocities from the long-term dataset, with a single locking point and two patches: (1) free slipping; (2) fully coupled. Green line is modeled shear component and red line is modeled shortening component. Using plate interface and dip models from Williams et al. (2013, Grey-dashed line) and the best fitting parameter ($\chi^2 = 2.17$), a locking depth of ~ 21 km was calculated. χ^2 is a measure of goodness of fit, based on the sum of the difference between the observed and expected calculated values. Shear components of nearby stations are projected plotted as black "Xs" and the shortening components are plotted as black diamonds. Vertical displacement (blue line) modeled but is not calculated. Seismicity plotted as small red dots (Eberhart-Phillips and Reyners, 2009).

Model 2 (inter-SSE velocities, Figure 6.16), shows a locking point depth of ~ 22 km, with a westward (negative direction) shift of 10 km, compared to model 1 (compare Figure 6.15 and 6.16). To some extent a horizontal shift can be recognized in Figure 6.12, by the westward movement of the shear strain rate inflection point. A locking depth of ~ 22 km is similar to previously derived depths by Darby and Beavan (2001) and Lamb and Smith (2013).

In order to constrain the effects of SSEs on total slip, a preliminary model 3 was generated with three patches: (1) fully coupled, (2) partially coupled, and (3) free slipping (Figure 6.14). Assuming a locking point depth of ~ 20 km (based on long-term velocity dislocation modeling, Figure 6.15), it was found that SSEs accommodate 65% of slip motion on the plate interface in this region during the epoch of the cGPS observations (Figure 6.14). We would expect that over longer time periods, when there is

Figure 6.16: Dislocation modeling results calculated using station velocities from the inter-SSE dataset, with a single locking point and two patches: (1) free slipping; (2) fully coupled. Using plate interface and dip models from Williams et al. (2013, Grey-dashed line) and the best fitting parameter ($\chi^2 = 2.97$), a locking depth of ~ 22 km was calculated. For other plot components see Figure 6.15.

enough time to average out SSEs, that the full plate velocity will be accommodated by slip on the subduction mega-thrust in the region of the SSEs.

6.6 Conclusions

In this study we determined strain rate parameters in central New Zealand, using three datasets of various station velocities: (1) long-term, (2) inter-SSE, and (3) co-seismic movement of the 2016 $M_W 7.8$ Kaikōura earthquake.

High shear strain rates in the Wellington and Cook Strait regions, overall compressional dilation, and overall positive (clockwise) vorticity was calculated using long-term cGPS station velocities (Figure 6.8). High shear strain rates in the Cook Strait region, overall compressional dilation, and overall positive (clockwise) vorticity was calculated using inter-SSE cGPS station velocities (Figure 6.9). These strain parameters best characterize what to expect over short time intervals (months to years).

Preliminary results showed the highest shear strain rates are coeval with surface ruptures and encompass the region with the highest rates of aftershocks of the Kaikōura

Figure 6.17: Dislocation modeling results calculated using station velocities from the inter-SSE dataset, with a two locking points and three patches: (1) free slipping; (2) partially coupled: 65%; (3) fully coupled. Using plate interface and dip models (Williams et al., 2013, , Grey-dashed line) and the best fitting parameter ($\chi^2 = 2.04$), a locking depth of 20.43 km was calculated. For other plot components see Figure 6.15.

earthquake. The extensional response to the Kaikōura earthquake in the eastern half of the southern North Island may have accommodated some of the accumulated stress due to the coupled plate interface.

The variation of the long-term and inter-SSE strain parameters indicates that the dynamics of locked portion of the southern Hikurangi subduction system not only vary on mega-thrust earthquake cycles (100s of years), but also on SSE time scales (<10 years). It is likely that the short-term dynamic changes of the couple zone would affect the characteristics (i.e., timing and hypocenter) of a subduction mega-thrust earthquakes and/or large crustal earthquakes (i.e. 2016 Kaikoura).

6.7 Acknowledgements

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viding the reference frame transformation codes.

Chapter 7

Conclusions

7.1 A Review of Stress Orientations and Strain Rates at the Southern Hikurangi Margin

Stress orientations, anisotropy, and strain parameters throughout the coupled region of the southern Hikurangi subduction zone have been investigated by comparing microseismicity, gravitational potential energy, shear-wave splitting, and cGPS data. This study provides observations, which will provide background information for a more robust and region specific seismic hazard assessment of the southern North Island, New Zealand and the subduction mega-thrust below.

7.1.1 Subducting Pacific Plate

Analysis within Chapters 3 and 4 characterize stress orientations of the double Benioff zone within the subducting Pacific plate, beneath the southern North Island. Stress orientations within the upper band of seismicity are consistent with an extensional regime (Figure 7.1). Stress orientations within the down-dip lower band of seismicity are consistent with a compressional regime (Figure 7.1). Stress orientations within the up-dip lower band of seismicity are consistent with an extensional regime (Figure 7.1). In the deeper region of the subduction zone, where there is upper extensional and lower compressional stress regimes, indicate bending forces. In the shallow region of the subduction zone, where there upper and lower extensional stress regimes, indicate slab-pull forces. Based on shape of the plate interface, it is likely that the bending stresses are also dominant within the slab in the northern region the Whanganui basin as well.

Coalescing of the two bands of seismicity in the deeper region of the double Benioff zone (Figure 4.2) could indicate that bending stresses are resulting in the loss of elastic strength throughout the subducting plate. Another possible explanation for the merging of the two bands of seismicity are that in all three previous DBZ studies (McGinty

et al. (2000); Du et al. (2004); this thesis) those earthquakes in the deeper reaches of the subduction zone have large depth uncertainties, because there are no seismometers directly above those earthquakes (i.e., all studies used only land based seismic stations).

7.1.2 Overriding Australian Plate

Analysis within Chapters 3, 5, and 6 characterized seismic anisotropy, stress orientations, and strain parameters in the overriding Australian plate at the southern North and northern South Islands. Observations of shear-wave splitting fast azimuth of N-S to NE-SW west of the Wairarapa fault is the result of structural sources (i.e. faults) and indicated shear deformation is the dominant factor (Figure 7.1). Within the Wairarapa Basin we observe an average fast azimuth orientation of NW-SE to NNW-SSE, near perpendicular to the Wairarapa fault and the subduction trench. Unlike west of the Wairarapa fault, within the Wairarapa basin, the fast azimuth is reflective of the SHmax orientation. A SHmax orientation of NW-SE to NNW-SSE and the prevalence of NNE-SSW trending reverse faulting indicate that shortening compressional deformation is dominant (Figure 7.1). In the eastern region of the southern North Island, deformation due to shearing and shortening is present (Figure 7.1). The stress field in this area is likely being complicated by large amounts of fluids with high fluid pressures (Reyners and Eberhart-Phillips, 2009; Bassett et al., 2014).

Although it is unclear to what extent, it seems likely that the underplated material (pink-region Figure 7.1), plays a significant role in the distribution of fluids (the strength of the upper plate) in the region. Based on interpretations of fluid distribution in the Rakaia and Pahua Terranes by Reyners and Eberhart-Phillips (2009) in relation to active faults mapped by Henrys et al. (2013), fluids from the subducting plate are predominantly flowing into the reverse fault zones, which initiate on the trenchward side of the underplated material surface within the Wairarapa basin.

Analysis of gravitational stress orientations in Chapter 3, show that GPE SHmax orientations west of the Wairarapa fault trend NE-SW, within the Wairarapa Basin trend NW-SE, and trend NE-SW in the eastern southern North Island (Figure 3.5 and 3.6). The similarity between the fast azimuth and gravitational SHmax orientations, in the Wairarapa basin, suggest that GPE stresses are a major component of the near surface stress field and should possibly be taken into account when assessing future seismic hazards in this region.

cGPS Strain Parameters

Analysis in Chapter 6 of inter-SSE (months-years) and long-term (years-decades) strain parameters, show increased rates of shear strain in the the Wellington and Cook Strait regions of the southern North Island (Figure 6.8, 6.9, 6.11-14). Inter-SSE and long-term strain parameters show southern North and northern South Island to be dominated by clockwise rotation and compressional dilatation. Preliminary dislocation models

showed there to be a difference between the effective locking point (point between couple and free-slip) depth of the plate interface of the couple zone when using long-term and inter-SSE cGPS datasets. This indicates that characteristics of the coupled zone dynamics not only vary on mega-thrust earthquake cycles (100s of years), but also on SSE time scales (<10 years). It would stand to reason that the short-term dynamic changes of the couple zone may effect how the zone reacts to subduction mega-thrust earthquakes and/or to large crustal earthquakes (i.e. 2016 Kaikoura).

Figure 7.1: (a) West of the Wairarapa fault (red-line) the fast azimuth orientation indicates the crust is dominated by simple shear deformation. Within the Wairarapa basin the fast azimuth orientation indicates the crust is dominated by compressional deformation. East of the Wairarapa basin compression and shear deformation is present. Crustal fluid distribution based on interpretations of Reyners and Eberhart-Phillips (2009); Bassett et al. (2014). Dashed-green line indicates cross-section location of (b). Active faults (grey-lines, <https://data.gns.cri.nz/af/>, Langridge et al. (2005)). (b) Adapted from Henrys et al. (2013) Figure 10. The north-west down-dip region of the subduction zone is dominated by bending stresses, juxtaposed to a underplated material (pink-region) and the Australian Moho. Dashed-black line shows extent of seismogenic thickness of the subducting Pacific plate. Red lines (purple for Wairarapa fault only) indicate active faults.

7.2 Overriding and Subducting Plate Interaction

Chapter 3, 4, and 5 demonstrates variations in the transfer of stresses between the subducting plate and the overriding plate, below the southern North Island, across the coupled region. Parallel trench plate motion is predominantly being accommodated west of the Wairarapa fault, where bending forces within the subducting plate are greatest and here is a transition from a coupled to freely-slipping plate interface (Figure 7.1). East of the Wairarapa fault, perpendicular trench motion is being accommodated by the shortening within the Wairarapa basin (Figure 7.1), above a region of the subducting plate that is dominated by slab-pull forces and coupling on the plate interface is greatest.

7.3 Future Work

The observation made in Chapter 4 (*Stress Orientations in a Double Benioff Zone: the Southern Hikurangi Margin, New Zealand*), combined with observations made during previous studies on the Hikurangi Subduction Zone further north, indicate that the dynamics of deformation within the subducting Pacific plate vary along the length of the southern Hikurangi Margin. A study of the northern extent of the southern Hikurangi Double Benioff Zone (HDBZ) would highlight the evolution of stresses within the subducting Pacific plate along the entirety of the New Zealand section of the southern Hikurangi Margin.

The observation made in Chapter 5 (*Crustal Anisotropy Across Southern North Island, New Zealand Revealed by a High Density Seismic Array*) showed that over relatively short distances the stress field can be governed by different factors. A study using an array designed with similar characteristics of the SAHKE II array, spanning various sections of the North Island, in turn traversing different sections of major fault systems, would allow for in-depth characterization of the evolution of stresses across the North Island. A study of this nature, when combined with the previously postulated study, would

allow for comprehensive study of the interactions of stresses within the subducting Pacific plate and the overriding Australian plate, further expanding upon the study done in Chapter 3 of this thesis.

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Chapter 8

Appendix A: Stress Orientations Throughout the Southern Hikurangi Margin

This chapter provides appendix material for Chapter 3: *Stress Orientations Throughout the Southern Hikurangi Margin*. Description of Content: The following includes figures of location and split of earthquakes used to determine the location of probable anisotropy, an enlarged version of a smaller figure in the paper that allows a more detailed look of the splitting results presented in the paper, a second cluster scheme and the resulting stress inversions (with an associated table), a table of focal mechanism parameters and tables of stress inversion results associated with the three clusters of inverted focal mechanisms.

Figure 8.1: Locations of earthquakes, above (orange) and below (green) 30 km, used to calculate fast directions. Bold grey lines show traces of active faults and topography on grey scale. A to A' shows orientation of cross sectional map. Cross-section: Cross sectional map from A to A', showing depth of earthquakes. Plate interface (black dashed line) calculated projected from Williams et al. (2013).

Figure 8.2: Enlarged version of Figure 3B. All (purple) and mean (yellow) fast direction measurements from earthquakes of all depths. Results show clear variation in splitting in the Western, Central Basin, and Eastern regions. Station S022 (highlighted dashed-red) is located near the Wairarapa fault. This station showed significant fast direction measurements parallel and perpendicular to the Wairarapa Fault. This effect is not present at other stations (S021, S023, LTN6, S039, HOWZ) (highlighted red).

Figure 8.3: Map of Bayesian calculated focal mechanisms and clusters of focal mechanisms, calculated using the K-means algorithm, used to calculate stress parameters. Red contours and grey faults are as in Figure 1. (A): SHmax (green) and 80% confidence intervals (black wedges), and associated clusters of focal mechanisms. Numbers next to cluster indicate cluster number. (B): Focal mechanisms calculated using a Bayesian method from Walsh et al. (2009). Focal mechanism are colored by rake: $-150^\circ < \text{Normal (red)} < -30^\circ$; $30^\circ < \text{Reverse (blue)} < 150^\circ$; $30^\circ > \text{Strike-Slip (green)} > -30^\circ$; $150^\circ < \text{Strike-Slip (purple)} < -150^\circ$. In total 314 focal mechanisms were calculated (181 normal, 30 reverse, and 103 strike-slip). Dashed A to A line indicates strike of cross-section map. Cross-section: Cross sectional map of focal mechanism with depth from A to A'. Dashed line (black) location is projected view of plate interface contours. (C) Rose diagram of average SHmax orientations in the three regions.

Figure 8.4: 20 stress regimes from the 20 clusters of focal mechanisms, shown as stereonet displaying the distribution of S1 (red), S2 (green), and S3 (blue) axes, as well as the orientation of SHmax axes (black dashed lines). The posterior mean (solid circle) and mode (open circle) are colored as per stress axis. The corresponding cluster color and number is printed below its stereonet. For locations of clusters see similar colored clusters in Figure S3. Number above stereonet indicates the stress ratio. Number following : indicates the number of focal mechanisms used in the stress inversion of the cluster.

Table 8.1: Stress inversion from the second cluster scheme of 20 clusters. Rows 5 and 6 are the bounds for the 80% confidence intervals for SHmax orientations.

Cluster	Parameter	Mean	Medium	X10	X90	Pink	Parameter	Mean	Medium	X10	X90
Red	S1	174.05	-6.96	-65.73	63.77		S1	26.51	26.90	-7.18	58.64
	S2	10.89	9.86	-38.92	66.11		S2	127.47	-53.22	-108.52	8.90
	S3	94.50	-87.14	-126.85	-37.17		S3	110.56	-69.41	-112.14	-26.79
	SHmax	178.75	178.77	136.32	220.68		SHmax	22.93	23.78	-10.39	54.07
	Stress Ratio	0.31	0.23	-0.02	0.78		Stress Ratio	0.59	0.63	0.12	0.96
Yellow	Parameter	Mean	Medium	X10	X90	Green	Parameter	Mean	Medium	X10	X90
	S1	78.88	79.39	15.45	144.44		S1	96.93	-80.89	-136.93	-33.47
	S2	67.25	68.51	46.29	86.96		S2	42.86	41.25	-6.34	99.72
	S3	157.90	-20.84	-42.96	-2.31		S3	139.40	-43.05	-73.27	0.64
	SHmax	68.97	69.92	48.09	87.88		SHmax	66.35	58.65	28.36	114.66
Cyan	Stress Ratio	0.38	0.37	0.10	0.66	Blue	Stress Ratio	0.50	0.50	0.02	0.96
	Parameter	Mean	Medium	X10	X90		Parameter	Mean	Medium	X10	X90
	S1	20.93	20.27	-46.71	94.92		S1	164.04	-14.17	-40.05	5.66
	S2	13.73	13.67	-24.34	51.16		S2	175.63	-3.47	-68.18	61.91
	S3	103.46	-75.90	-113.03	-42.22		S3	80.92	79.47	56.04	107.34
Purple	SHmax	12.42	13.56	-25.18	46.67	Brown	SHmax	166.24	167.14	143.90	187.22
	Stress Ratio	0.52	0.54	0.19	0.81		Stress Ratio	0.66	0.69	0.39	0.89
	Parameter	Mean	Medium	X10	X90		Parameter	Mean	Medium	X10	X90
	S1	53.11	53.08	-3.04	111.32		S1	131.70	-46.96	-95.06	6.33
	S2	40.23	39.96	16.41	63.85		S2	58.59	58.61	43.24	73.98

Table 8.1 continued from previous page

Sea Green	S3	130.73	-49.33	-71.38	-27.35	S3	150.04	-30.08	-43.63	-16.11
	SHmax	41.96	41.39	20.26	63.23	SHmax	60.21	60.06	46.68	73.44
	Stress Ratio	0.50	0.49	0.15	0.86	Stress Ratio	0.29	0.28	0.15	0.43
	Parameter	Mean	Medium	X10	X90	Parameter	Mean	Medium	X10	X90
	S1	113.20	-65.27	-107.22	-32.09	S1	110.07	-72.46	-103.86	-29.38
Grey	S2	54.40	54.27	5.29	105.98	S2	37.12	37.15	21.22	52.94
	S3	149.58	-30.81	-80.71	23.73	S3	132.72	-47.24	-62.41	-32.28
	SHmax	90.91	92.11	39.10	139.31	SHmax	43.70	43.86	29.06	57.59
	Stress Ratio	0.80	0.85	0.52	0.98	Stress Ratio	0.42	0.41	0.25	0.60
	Parameter	Mean	Medium	X10	X90	Parameter	Mean	Medium	X10	X90
Light Blue	S1	75.61	74.41	39.98	123.41	S1	89.95	-92.68	-113.85	-61.62
	S2	25.69	26.83	0.12	49.11	S2	29.48	15.62	-4.10	97.88
	S3	125.04	-54.18	-75.96	-34.53	S3	106.91	-77.01	-90.00	-60.81
	SHmax	36.22	37.16	16.38	55.48	SHmax	36.72	26.24	8.28	91.41
	Stress Ratio	0.26	0.23	0.09	0.49	Stress Ratio	0.84	0.86	0.72	0.93
Orange	Parameter	Mean	Medium	X10	X90	Parameter	Mean	Medium	X10	X90
	S1	39.36	38.41	-2.19	85.59	S1	28.50	29.93	-41.04	98.39
	S2	30.53	29.15	-23.93	91.72	S2	96.44	-84.44	-138.99	-23.18
	S3	117.95	-62.53	-111.50	-10.81	S3	5.59	4.49	-48.85	65.75
	SHmax	29.90	30.82	-10.39	67.10	SHmax	80.41	82.25	13.39	146.54
Tan	Stress Ratio	0.70	0.72	0.42	0.95	Stress Ratio	0.74	0.82	0.31	0.98
	Parameter	Mean	Medium	X10	X90	Parameter	Mean	Medium	X10	X90
	S1	38.16	41.11	-31.60	104.84	S1	69.68	67.59	40.56	107.89
	S2	30.53	29.15	-23.93	91.72	S2	96.44	-84.44	-138.99	-23.18
	S3	117.95	-62.53	-111.50	-10.81	S3	5.59	4.49	-48.85	65.75
Rosy Brown	SHmax	29.90	30.82	-10.39	67.10	SHmax	80.41	82.25	13.39	146.54
	Stress Ratio	0.70	0.72	0.42	0.95	Stress Ratio	0.74	0.82	0.31	0.98
	Parameter	Mean	Medium	X10	X90	Parameter	Mean	Medium	X10	X90
	S1	38.16	41.11	-31.60	104.84	S1	69.68	67.59	40.56	107.89
	S2	30.53	29.15	-23.93	91.72	S2	96.44	-84.44	-138.99	-23.18
Coral	S3	117.95	-62.53	-111.50	-10.81	S3	5.59	4.49	-48.85	65.75
	SHmax	29.90	30.82	-10.39	67.10	SHmax	80.41	82.25	13.39	146.54
	Stress Ratio	0.70	0.72	0.42	0.95	Stress Ratio	0.74	0.82	0.31	0.98
	Parameter	Mean	Medium	X10	X90	Parameter	Mean	Medium	X10	X90
	S1	38.16	41.11	-31.60	104.84	S1	69.68	67.59	40.56	107.89

Table 8.1 continued from previous page

Plum	S2	40.87	39.80	-8.43	97.40	Dark Orange	S2	54.98	55.22	16.82	92.02
	S3	134.51	-46.81	-100.29	17.59		S3	150.46	-29.47	-44.15	-15.13
	SHmax	36.58	38.40	-12.50	81.37		SHmax	60.77	60.41	47.73	73.44
	Stress Ratio	0.80	0.93	0.30	0.99		Stress Ratio	0.12	0.09	-0.04	0.30
	Parameter	Mean	Medium	X10	X90		Parameter	Mean	Medium	X10	X90
	S1	88.33	-92.83	-135.81	-42.34		S1	36.94	35.28	2.37	76.71
	S2	63.37	63.00	36.34	90.56		S2	22.61	22.24	-39.08	87.64
	S3	157.42	-22.30	-41.23	-4.26		S3	127.74	-53.35	-83.77	-18.73
	SHmax	70.07	69.92	53.02	86.83		SHmax	37.90	35.75	5.46	74.15
	Stress Ratio	0.26	0.22	-0.02	0.61		Stress Ratio	0.40	0.32	0.08	0.86
	Parameter	Mean	Medium	X10	X90		Parameter	Mean	Medium	X10	X90
	S1	15.86	15.65	-27.47	61.08		S1	163.24	-17.76	-39.91	7.87
Magenta	S2	20.56	20.25	1.71	39.75	Chocolate	S2	160.85	-19.15	-57.73	18.80
	S3	109.27	-70.90	-86.28	-55.01		S3	69.86	70.29	51.14	88.26
	SHmax	18.76	18.49	4.76	32.58		SHmax	160.94	161.15	143.55	177.71
	Stress Ratio	0.19	0.16	-0.04	0.46		Stress Ratio	0.24	0.21	0.03	0.51
	Parameter	Mean	Medium	X10	X90		Parameter	Mean	Medium	X10	X90
	S1	15.86	15.65	-27.47	61.08		S1	163.24	-17.76	-39.91	7.87

Table 8.2: Parameters of focal mechanisms used in stress inversion in Chapter 3: *Stress Orientations Throughout the Southern Hikurangi Margin*

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
174.44	-41.26	36.65	319.23	80.41	-3.85	175.61	-40.97	29.73	105.20	43.29	9.79
174.63	-41.63	31.56	292.08	45.69	65.37	175.79	-40.87	26.90	42.33	31.42	-45.85
174.79	-41.45	32.39	238.98	68.36	-56.24	175.97	-41.02	30.77	174.97	65.33	-159.75
175.65	-41.13	21.34	109.04	86.81	67.62	175.31	-40.97	20.86	118.11	19.19	162.18
175.61	-41.53	24.16	349.34	43.50	-56.05	176.03	-40.93	35.82	166.77	38.72	-119.77
175.28	-41.26	32.47	215.26	67.71	-111.66	175.44	-40.85	26.17	128.47	24.34	-56.86
174.79	-41.09	29.32	59.72	55.29	-83.44	175.27	-41.27	31.88	210.30	51.98	-86.68
175.30	-40.93	30.91	40.91	28.09	-146.80	175.48	-41.09	29.52	38.76	43.11	-132.28
175.03	-40.70	33.04	107.05	25.44	-156.34	174.83	-41.06	30.44	213.41	31.79	-98.86
174.93	-40.98	28.96	40.00	50.56	-96.23	175.18	-41.27	28.85	345.15	36.93	-159.73
174.82	-41.22	34.08	24.15	30.17	-122.18	174.78	-41.29	28.17	230.71	42.12	-129.55
175.31	-41.25	29.09	229.47	82.25	-112.10	175.40	-40.99	28.97	254.89	87.88	-96.09
175.50	-40.85	23.27	256.58	67.39	-82.06	175.28	-40.76	34.99	90.67	42.57	-23.29
175.09	-40.79	39.34	246.23	79.05	-116.89	175.32	-41.27	22.09	287.38	27.95	-0.36
175.35	-41.01	30.43	31.34	25.55	-67.76	176.08	-40.87	32.57	267.03	87.01	39.73
175.46	-41.08	29.45	74.77	33.02	-76.41	175.29	-41.55	27.24	5.35	35.31	-84.60
175.21	-40.98	29.92	45.86	31.82	173.03	175.42	-40.99	26.17	44.43	27.46	-93.36
174.46	-41.06	42.41	99.60	28.61	8.68	175.49	-40.93	21.78	240.89	54.60	-51.36
175.94	-40.85	32.69	135.21	42.31	166.11	174.67	-41.05	28.12	265.86	23.59	-13.34
175.58	-40.98	26.89	41.35	15.75	-96.62	174.72	-41.63	29.33	187.42	39.54	-60.09
175.06	-41.05	28.59	29.74	31.53	-86.94	175.50	-40.90	21.47	350.58	55.67	-138.66

Table 8.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
175.67	-40.88	29.15	115.79	21.56	-63.46	175.34	-41.05	30.21	54.99	15.09	-121.76
174.82	-41.24	25.80	356.93	48.30	-3.50	175.41	-41.00	28.80	119.80	15.44	17.08
175.11	-41.34	31.03	316.33	25.31	-167.42	175.04	-41.06	29.00	44.55	19.96	-93.88
174.86	-40.92	30.92	255.86	57.07	-66.62	175.19	-40.89	27.22	85.72	27.17	-48.18
175.65	-41.05	49.77	187.00	32.62	-159.37	174.95	-41.06	33.21	271.11	16.15	-174.34
175.22	-41.26	31.01	57.38	89.20	108.13	174.64	-41.42	32.75	341.71	54.71	137.15
175.05	-41.05	28.68	246.69	68.17	-92.45	175.27	-40.91	31.35	107.29	48.29	-37.42
174.63	-41.42	31.15	49.92	60.89	-171.22	176.31	-40.80	26.31	12.92	27.74	-79.75
175.58	-40.96	28.28	259.81	54.50	-53.24	176.06	-40.89	28.96	335.93	87.64	18.39
175.58	-40.95	29.50	265.40	43.95	-75.31	176.08	-40.89	31.56	338.84	34.73	-103.25
174.90	-41.32	30.72	344.90	57.70	-141.79	174.68	-41.06	29.27	293.63	7.31	172.09
175.05	-41.05	28.63	40.60	26.58	-105.35	175.16	-40.92	25.74	242.20	79.46	-89.13
175.22	-41.09	27.95	312.64	32.23	-159.81	175.78	-40.74	28.74	37.27	51.22	179.74
175.56	-41.55	14.36	192.12	72.63	16.52	175.04	-41.06	27.63	259.43	84.64	-76.92
175.27	-41.28	32.21	101.93	7.73	-41.45	175.28	-40.80	27.33	214.00	67.13	-149.77
174.60	-41.09	28.59	285.00	11.53	-3.26	175.29	-40.80	26.42	107.12	53.90	-14.83
175.01	-41.06	29.59	197.15	43.90	-117.00	175.29	-40.81	26.67	242.90	71.11	-114.72
175.09	-41.36	29.28	330.36	25.86	-21.92	174.99	-41.34	30.41	338.77	38.21	-147.57
175.40	-40.98	30.92	125.34	39.35	177.64	174.84	-40.92	52.05	141.79	10.27	156.83
175.08	-41.36	31.96	22.30	77.00	72.24	175.00	-41.34	30.12	343.42	28.25	-149.27
175.02	-41.24	28.63	18.77	16.52	-97.08	174.42	-41.19	37.23	358.68	85.04	-117.86
175.23	-41.25	31.00	11.41	14.12	-41.51	174.72	-41.63	29.68	321.98	74.01	-172.67

Table 8.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
175.27	-41.27	32.61	1.14	80.71	0.47	175.64	-40.94	27.17	132.49	32.10	-170.93
174.97	-40.84	39.98	103.90	22.08	-160.50	175.24	-41.21	26.08	81.54	16.71	-51.62
175.21	-41.25	30.76	351.22	20.14	-22.97	175.44	-40.77	26.55	242.63	71.88	-90.79
175.69	-40.79	22.89	340.94	26.28	-130.42	174.99	-41.34	30.42	338.45	30.22	-34.67
175.42	-40.89	17.78	298.71	82.29	-1.11	175.85	-41.09	26.59	29.91	79.52	-163.32
176.49	-40.70	18.06	153.05	52.11	38.86	175.09	-40.80	33.86	228.34	37.43	-117.26
175.46	-41.08	29.16	352.32	74.91	167.18	175.05	-41.06	29.46	25.62	18.04	-101.48
175.22	-41.26	22.77	85.18	8.66	-131.82	174.79	-41.31	30.38	195.16	55.23	-111.73
175.04	-41.24	28.35	316.25	21.25	159.41	175.47	-41.06	29.88	25.86	46.12	-138.35
175.03	-41.06	28.43	38.13	20.80	-120.90	175.47	-41.06	26.78	270.26	86.54	-39.57
175.05	-41.05	29.00	216.46	47.73	-133.11	175.28	-41.28	31.35	28.78	32.74	-119.94
175.44	-41.02	31.79	131.54	37.75	-24.55	175.19	-41.27	26.59	275.37	4.95	28.66
175.76	-40.80	29.58	51.17	39.52	-160.70	175.71	-40.86	26.28	27.27	37.59	-132.00
175.60	-41.35	19.77	148.44	25.01	170.73	174.56	-41.22	26.30	181.08	81.29	-53.91
175.31	-41.23	31.19	241.44	87.09	-96.95	175.48	-40.78	25.12	19.63	74.00	164.38
175.30	-41.24	27.54	88.13	78.55	-47.13	175.23	-41.63	17.50	275.87	68.43	-148.36
175.28	-41.27	32.52	37.25	8.71	-61.17	174.66	-41.11	28.10	334.40	18.84	-39.16
175.17	-41.57	20.20	163.00	22.97	167.36	175.05	-41.07	29.70	17.24	28.55	-87.56
175.17	-41.58	19.08	239.87	18.41	80.17	174.89	-41.39	19.69	107.20	41.89	-70.28
175.23	-41.08	28.06	133.90	25.04	-165.93	174.72	-40.85	48.43	28.13	67.49	21.85
175.50	-40.86	27.01	218.81	72.23	-132.77	175.27	-40.97	45.81	192.18	73.81	-117.63
174.81	-41.27	30.69	325.45	40.69	-171.00	175.61	-40.90	25.32	179.26	51.02	-121.94

Table 8.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
175.17	-41.57	20.00	273.54	78.93	-143.26	175.64	-40.93	26.02	270.63	65.40	-159.32
175.17	-41.57	20.01	288.77	36.81	123.46	175.42	-40.94	24.11	242.45	66.31	-122.38
174.45	-40.98	39.34	272.02	83.61	-18.21	175.41	-40.99	25.96	119.01	51.54	-22.13
175.49	-40.86	24.42	114.33	64.61	-32.48	175.56	-41.30	20.49	203.93	11.06	81.90
175.03	-41.06	28.81	205.20	42.11	-117.85	174.80	-41.08	27.86	245.35	64.00	-44.64
174.56	-41.23	25.45	326.04	49.74	-138.78	174.74	-40.98	29.09	270.54	43.34	-36.61
175.40	-41.00	29.12	232.88	75.56	-107.89	175.52	-40.85	22.69	59.82	25.10	-110.16
175.00	-41.10	31.60	27.02	21.38	-116.65	175.64	-40.86	24.27	211.44	71.36	-156.63
174.48	-41.71	31.76	161.80	42.29	126.69	175.50	-40.87	16.40	144.81	82.65	-8.35
175.59	-41.27	18.39	206.93	79.70	-100.83	175.57	-41.13	21.32	176.94	33.82	51.63
174.92	-41.11	38.33	263.57	77.65	-72.03	175.28	-40.75	29.30	288.41	87.27	-79.95
176.55	-41.25	42.30	36.90	46.44	-60.34	175.03	-41.06	30.91	234.71	45.26	-72.11
176.33	-41.25	38.83	164.25	56.07	-160.69	175.04	-41.37	42.26	318.33	36.64	27.45
176.41	-41.19	41.70	170.26	44.92	-123.91	175.95	-40.66	25.38	10.63	38.21	-106.19
174.86	-41.05	30.97	10.60	48.36	-145.67	175.71	-40.85	28.98	172.85	17.12	-35.83
175.50	-40.98	25.25	99.24	63.42	-52.19	175.80	-40.82	29.27	239.07	46.74	-38.88
175.65	-40.87	25.84	153.85	57.85	156.07	174.63	-41.43	32.16	340.73	26.95	-123.58
176.25	-40.77	28.20	264.26	54.88	-176.95	176.11	-40.82	36.09	329.74	77.99	132.98
175.23	-41.24	28.40	138.96	15.40	9.10	174.97	-41.40	30.98	244.61	78.68	-61.71
175.06	-41.37	32.04	356.29	16.17	-53.02	175.57	-40.95	28.28	64.80	85.95	78.14
175.38	-41.22	23.52	140.35	29.01	-15.25	174.85	-40.95	28.19	194.87	31.80	-105.55
176.19	-41.33	35.43	55.74	46.43	-57.67	174.50	-41.39	25.56	251.24	36.46	-40.35

Table 8.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
176.32	-41.17	39.48	173.00	45.21	-117.95	175.41	-41.20	24.50	124.93	36.70	8.71
175.69	-41.23	27.56	203.54	32.20	-74.00	174.58	-40.86	36.01	9.27	17.50	73.28
176.53	-41.14	37.74	184.45	44.23	-125.62	174.72	-40.77	40.33	30.26	63.30	-141.71
175.71	-40.97	36.74	174.59	7.75	-112.20	174.99	-41.26	30.24	5.15	35.82	-144.57
176.55	-41.12	40.01	7.31	37.86	-82.05	174.72	-40.94	32.98	33.30	53.60	-143.04
176.32	-41.16	37.72	182.58	34.16	-116.36	175.61	-41.52	26.42	240.00	42.96	-57.77
174.60	-40.94	46.15	358.15	29.29	-128.18	174.47	-41.14	29.70	331.13	70.49	-167.90
176.17	-41.31	35.87	13.62	51.25	-96.26	175.43	-41.14	20.97	31.05	77.33	81.12
176.15	-41.32	37.24	185.30	87.79	153.62	175.47	-41.08	29.56	144.20	11.15	161.60
175.68	-40.88	27.64	144.16	21.35	140.99	175.32	-41.23	29.49	227.36	63.59	-87.83
175.57	-40.93	31.52	215.20	46.37	-27.20	175.71	-41.72	41.35	156.15	76.71	159.33
174.89	-40.91	33.20	58.88	50.54	-95.86	175.96	-40.90	18.84	167.17	69.85	23.21
174.90	-40.92	31.99	243.83	35.87	-79.66	175.13	-41.23	27.27	315.27	48.85	-146.84
176.14	-41.32	36.99	197.77	31.28	-86.11	175.21	-40.91	32.18	64.87	48.49	-83.91
176.16	-41.31	37.35	206.80	31.91	-80.08	175.85	-40.83	33.39	323.14	76.54	-21.29
176.15	-41.31	37.13	155.81	82.06	164.24	175.08	-41.31	28.22	114.08	38.87	-68.71
175.53	-41.41	18.51	23.82	15.29	-83.55	175.56	-40.96	30.01	270.38	70.52	-56.43
175.33	-41.27	25.50	289.15	19.00	147.83	175.81	-40.85	26.76	194.26	28.81	-63.18
175.51	-40.90	23.43	124.55	50.89	2.50	175.88	-40.80	33.17	165.62	53.49	-56.82
174.89	-40.91	32.54	44.18	56.98	-98.78	174.72	-41.12	27.70	354.81	27.08	-127.05
175.03	-41.06	29.36	117.46	20.67	-166.89	174.54	-41.77	28.49	148.92	45.70	117.75
175.22	-41.20	29.08	22.26	5.97	-70.10	175.50	-41.47	26.11	30.20	32.33	-112.70

Table 8.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
175.57	-40.94	30.54	66.05	50.28	-38.86	175.10	-41.04	29.36	231.05	67.59	-128.39
175.23	-41.23	28.54	125.11	10.94	-177.61	175.08	-41.38	31.79	84.36	20.14	-33.14
175.23	-41.24	28.32	110.06	7.81	-158.19	175.20	-41.64	16.82	249.32	47.83	-15.49
175.23	-41.24	27.81	126.28	7.75	-177.99	175.61	-41.12	20.27	105.00	16.35	-15.43
174.89	-40.91	31.97	287.43	48.60	-66.39	175.52	-40.86	25.38	106.88	47.44	-20.23
175.58	-40.96	29.40	252.94	50.60	-75.72	175.19	-41.64	17.30	351.23	87.07	16.38
175.47	-40.81	23.97	58.03	34.55	-108.58	175.26	-41.27	31.42	42.62	79.12	49.61
175.23	-41.23	27.97	220.00	89.03	-93.30	175.01	-41.28	27.57	62.12	88.72	35.43
176.33	-41.62	43.06	21.55	77.04	148.76	176.08	-40.85	26.90	337.13	46.69	-26.03
175.01	-40.94	44.27	138.89	52.06	152.72	175.05	-40.78	29.56	240.39	21.06	-118.72
174.56	-41.08	28.80	326.50	62.85	-22.25	175.06	-41.06	29.13	340.80	33.67	-13.87
175.23	-41.24	27.24	340.52	17.45	-28.66	175.55	-40.96	29.18	349.48	44.95	-144.38
174.93	-41.42	33.34	237.09	29.92	-128.95	174.73	-40.99	28.32	259.35	11.59	-122.24
174.94	-41.43	26.95	312.67	38.92	-19.51	175.08	-41.36	30.62	302.03	64.64	-31.48
174.88	-40.91	30.77	55.10	51.03	-95.99	175.50	-40.85	24.23	114.29	52.61	39.67
174.89	-40.90	31.41	56.44	45.40	-106.62	174.88	-41.40	33.42	217.22	66.22	-135.35
174.88	-40.90	32.21	235.78	33.97	-87.33	174.82	-41.05	31.80	11.65	26.19	-108.19
175.11	-41.34	31.80	212.84	75.25	-108.05	175.28	-40.69	38.13	81.98	33.05	-68.29
176.25	-41.57	42.58	31.09	52.46	-131.02	175.24	-41.20	28.34	166.28	21.55	138.87
176.03	-40.86	26.58	334.76	77.00	-176.66	174.92	-40.84	40.43	106.28	24.94	-98.04
176.53	-41.20	44.59	153.19	55.35	-157.76	175.35	-41.65	34.28	282.01	54.57	-15.81
176.13	-41.32	33.31	7.02	34.28	-91.40	175.09	-41.36	31.26	121.55	41.71	13.92

Table 8.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
175.09	-41.26	27.32	223.85	62.59	-113.54	175.05	-41.04	26.78	196.01	46.78	-136.84
174.81	-41.26	51.00	83.23	56.43	-108.02	175.19	-41.19	31.15	230.98	61.01	-115.64
175.53	-40.93	28.40	35.29	54.76	-135.56	174.94	-41.27	29.72	345.16	20.66	-156.99
175.06	-41.05	29.96	229.92	58.90	-81.05	175.96	-41.02	27.52	58.16	71.26	-99.30
175.06	-41.05	31.09	54.26	28.09	-78.92	176.04	-40.90	26.61	337.63	48.24	-18.34
175.50	-41.47	26.51	39.04	36.01	-107.94	175.05	-40.72	31.54	235.89	47.65	-117.94
175.78	-40.89	34.33	262.02	77.07	-8.55	175.32	-40.90	25.04	43.51	40.11	-108.43
174.53	-41.36	24.77	173.74	72.18	-121.97	175.09	-41.37	31.20	328.87	38.02	165.12
174.82	-40.92	34.48	53.30	41.97	-155.99	174.74	-41.63	30.56	148.44	69.70	-151.05
174.78	-41.32	47.94	9.81	37.44	7.47	174.88	-40.94	33.82	196.45	41.85	-81.03
174.93	-41.35	18.65	123.67	39.34	-26.32	175.06	-41.04	25.52	353.83	33.34	-64.64
175.18	-40.88	30.27	191.47	46.25	-128.95	174.76	-41.17	38.33	159.34	89.77	-163.42
174.63	-41.05	33.06	175.66	7.46	117.82	176.00	-40.93	25.72	177.48	72.14	175.82
174.72	-41.00	28.48	26.87	68.47	-124.68	175.22	-41.24	27.95	169.55	8.31	46.41
175.28	-41.27	28.74	281.94	10.66	38.43	175.06	-41.04	28.08	215.21	43.72	-122.32
175.74	-40.82	29.25	143.81	56.33	-88.55	175.22	-41.24	27.82	202.58	83.57	-132.72
175.23	-41.24	28.37	126.35	8.43	-173.13	175.25	-41.25	26.67	100.22	82.25	15.17
176.19	-40.70	31.25	145.51	40.36	-49.04	175.59	-40.97	31.17	66.24	37.05	-96.81
175.28	-41.27	30.30	223.79	78.35	-104.59	175.62	-40.94	27.46	45.17	16.41	-100.93
175.81	-40.85	28.32	267.78	66.03	52.98	175.17	-41.21	34.34	226.61	52.92	-133.80
175.27	-41.21	30.44	237.69	78.02	-99.34	175.05	-41.11	21.50	320.99	81.60	175.69
175.48	-40.85	17.35	220.25	79.68	-1.00	176.10	-40.85	22.74	338.73	74.29	170.98

Table 8.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
175.33	-41.06	29.33	195.89	6.74	59.18	175.18	-41.21	31.11	179.67	37.84	-178.42
174.90	-41.19	22.95	47.80	18.07	-127.99	174.90	-40.92	31.83	65.96	44.20	-140.66
176.17	-40.86	26.99	280.52	52.60	-170.12	174.69	-41.01	29.59	146.84	70.19	137.45
176.16	-40.87	28.02	278.74	51.05	-172.19	175.74	-40.80	26.99	321.87	34.19	-74.56

Table 8.3: Results of stress inversion for the Western Region of the study region. Mean and Medium values calculated using the Bayesian method. X2.5 and X97.5 indicate the 95% confidence interval bounds. Map indicated parameters calculated using the Map method, embedded in the Bayesian program (for comparisons only).

Parameter	Mean	Map	Median	X2.5	X97.5
S1	137.62	141.92	-41.85	-97.35	14.77
S2	51.38	51.92	51.44	33.45	68.96
S3	143.29	141.92	-36.63	-52.55	-21.35
SHmax	53.13	54.00	53.01	36.11	69.56
Nu	0.37	0.40	0.38	0.26	0.51

Table 8.4: Results of stress inversion for the Central Basin Region of the study region. Mean and Medium values calculated using the Bayesian method. X2.5 and X97.5 indicate the 95% confidence interval bounds. Map indicated parameters calculated using the Map method, embedded in the Bayesian program (for comparisons only).

Parameter	Mean	Map	Median	X2.5	X97.5
S1	72.57	72.69	71.56	35.87	120.54
S2	36.89	34.62	36.23	20.47	59.69
S3	124.03	121.15	-56.61	-73.15	-33.47
SHmax	36.51	37.33	36.11	19.91	53.36
Nu	0.61	0.60	0.60	0.46	0.74

Table 8.5: Results of stress inversion for the Eastern Region of the study region. Mean and Medium values calculated using the Bayesian method. X2.5 and X97.5 indicate the 95% confidence interval bounds. Map indicated parameters calculated using the Map method, embedded in the Bayesian program (for comparisons only).

Parameter	Mean	Map	Median	X2.5	X97.5
S1	146.36	148.85	-32.61	-74.40	1.70
S2	168.57	169.62	-11.47	-52.49	28.99
S3	71.64	72.69	71.96	39.13	101.97
SHmax	158.18	156.59	158.34	127.69	186.51
Nu	0.53	0.50	0.53	0.25	0.81

Chapter 9

Appendix B: Illumination of Deformation by Bending Stresses within the Southern Hikurangi Double Benioff Zone

This chapter provides appendix material for Chapter 4: *Stress Orientations in a Double Benioff Zone*. Description of Content: The following includes a table of focal mechanism parameters and tables of stress inversion parameter results associated with the three clusters of inverted focal mechanisms. Figures showing the difference between this study's region of interest and the study region of McGinty et al. (2000) and comparison of the radius of curvature of the subducting Pacific plate at the southern North Island and the northern South Island. The three additional stress inversions (and parameters) of the clusters of focal mechanisms, regardless of number of polarity picks.

Table 9.1: Earthquake magnitude distribution. No magnitudes were calculated during this study, earthquake magnitude calculated by GeoNet.

Magnitude	# of Earthquakes
< 1.50	01
1.50 - 1.75	15
1.75 - 2.00	69
2.00 - 2.25	179
2.25 - 2.50	186
2.50 - 2.75	112
2.75 - 3.00	56
3.00 - 3.25	28
3.25 - 3.50	11
3.50 - 3.75	12
3.75 - 4.00	03
4.00 - 4.25	04
4.25 - 4.50	03
4.50 - 4.75	01
> 4.75	00

Table 9.2: Parameters of focal mechanisms used in stress inversion in Chapter 4: *Stress Orientations in a Double Benioff Zone*

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
174.53	-41.32	33.76	300.02	37.99	-0.70	174.25	-40.88	36.82	149.21	38.92	-134.19
175.01	-40.49	23.80	148.58	68.22	-1.21	173.50	-40.54	160.16	195.07	78.25	-134.51
174.66	-41.08	33.36	109.36	22.38	-1.22	173.70	-41.34	75.20	30.19	68.69	-134.97
174.60	-41.10	58.37	3.52	79.62	-1.58	174.66	-41.16	39.84	32.87	6.14	-134.97
174.19	-40.77	69.24	325.75	86.21	-2.07	175.56	-40.95	30.61	337.60	54.43	-136.13
174.70	-41.43	37.70	344.63	84.92	-2.89	174.97	-40.90	46.51	24.15	26.24	-136.82
174.60	-40.99	34.44	77.88	28.60	-3.03	175.34	-40.57	33.66	197.58	67.88	-137.31
174.41	-40.96	51.73	338.19	42.77	-5.24	176.18	-40.60	34.99	258.24	47.13	-137.72
174.70	-41.42	34.53	346.98	85.08	-5.67	174.69	-40.66	29.61	202.43	78.45	-137.87
175.10	-40.80	34.13	84.05	35.83	-5.76	175.84	-40.52	42.30	192.75	60.88	-138.41
175.97	-40.55	32.18	355.64	79.10	-6.62	174.77	-40.48	2.99	49.03	81.64	-138.48
175.37	-40.59	30.77	210.45	69.95	-6.69	175.32	-40.68	23.86	173.86	81.64	-139.01
174.28	-41.42	66.87	28.94	80.90	-6.87	175.30	-40.85	31.10	232.39	51.43	-139.60
175.89	-40.67	34.73	138.30	50.10	-6.92	174.39	-40.89	67.90	45.48	62.21	-141.18
174.64	-40.94	73.79	42.86	37.77	-8.46	174.72	-41.45	32.39	8.58	74.97	-142.00
174.53	-40.99	37.79	335.87	47.27	-8.48	173.81	-40.96	71.06	66.82	44.69	-142.63
174.43	-41.13	46.61	97.69	43.79	-9.46	174.93	-40.81	39.99	214.42	82.10	-142.67
173.97	-40.57	101.75	332.74	31.19	-9.57	173.88	-40.58	111.23	343.93	28.31	-143.09
176.20	-40.57	26.70	145.11	52.42	-10.30	175.88	-40.59	35.01	20.77	49.38	-143.79
174.34	-40.52	63.19	5.18	54.68	-11.71	174.35	-40.46	18.75	19.10	32.06	-144.37
173.98	-40.77	34.54	16.80	86.97	-11.75	173.92	-41.43	45.63	170.32	45.55	-145.51

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
174.48	-41.21	39.10	288.55	44.45	-11.78	176.10	-40.90	30.32	181.03	40.72	-146.04
173.92	-40.55	101.50	116.35	65.03	-13.96	174.69	-41.43	34.64	47.27	48.42	-146.49
174.17	-41.49	47.22	132.61	47.09	-15.10	174.73	-40.47	16.46	210.81	48.18	-147.69
174.51	-40.66	71.05	191.31	22.82	-15.40	175.27	-40.76	35.23	200.02	69.76	-147.80
175.91	-40.49	33.01	335.50	7.43	-15.77	174.42	-40.52	31.62	191.19	55.29	-147.82
174.19	-40.93	49.53	304.38	68.48	-16.42	175.68	-41.05	52.29	196.20	33.56	-148.05
175.11	-40.71	29.25	195.39	57.13	-16.99	176.19	-40.83	32.16	25.44	24.04	-148.38
173.59	-41.21	64.59	177.73	33.14	-18.12	173.57	-40.67	109.35	182.75	32.50	-148.41
174.44	-40.55	93.16	303.95	41.16	-18.22	175.33	-40.43	23.77	184.04	75.00	-148.52
175.49	-40.58	27.10	288.38	56.88	-18.41	174.27	-40.94	35.88	188.90	43.32	-148.65
174.59	-40.82	44.00	121.15	34.04	-18.99	174.92	-41.39	33.54	217.02	68.68	-148.82
174.01	-40.79	97.89	325.77	85.26	-19.00	174.62	-40.81	72.04	18.21	2.41	-148.96
174.86	-40.63	29.29	154.59	51.53	-19.47	174.46	-41.10	37.07	47.98	27.20	-149.67
175.95	-40.69	32.88	220.31	48.67	-19.56	175.99	-40.58	31.97	321.91	31.39	-149.96
174.70	-41.42	35.72	276.30	54.11	-19.73	174.79	-41.01	58.10	4.30	24.34	-150.71
174.69	-41.45	33.94	167.87	63.71	-20.65	173.91	-41.49	39.67	18.84	48.52	-150.77
174.07	-41.45	44.50	279.18	88.98	-21.34	174.68	-41.20	54.28	213.96	66.07	-150.91
173.48	-41.10	102.87	170.79	77.02	-24.02	174.50	-41.05	35.62	315.70	18.97	-151.04
175.30	-41.01	36.40	350.47	7.33	-24.05	173.92	-41.49	49.62	9.50	58.13	-152.55
175.20	-40.77	30.72	218.91	51.02	-24.05	174.43	-40.95	42.19	35.72	47.66	-153.20
174.18	-40.57	64.97	100.31	70.35	-24.24	174.73	-41.15	29.36	82.52	27.31	-153.88
176.22	-40.53	25.44	112.66	46.82	-24.28	174.66	-40.88	69.40	11.61	56.48	-153.89

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
173.56	-41.13	98.45	326.37	77.88	-24.44	174.76	-41.01	54.58	320.88	51.84	-154.23
175.01	-40.91	60.64	283.69	86.79	-25.20	174.23	-40.56	97.00	116.76	5.92	-155.38
173.62	-41.43	82.10	294.04	57.62	-25.25	174.61	-41.35	58.06	13.34	44.51	-155.50
174.82	-40.93	34.64	42.46	41.40	-25.51	174.47	-40.45	1.47	226.52	39.57	-155.92
174.46	-41.19	36.00	265.13	52.42	-25.95	174.24	-40.65	87.34	71.08	46.35	-156.10
173.55	-41.18	71.59	291.66	42.47	-26.13	174.21	-40.62	78.83	336.02	84.81	-156.51
174.92	-41.14	38.28	344.51	41.92	-26.28	174.62	-41.24	54.70	24.50	66.71	-156.56
176.22	-40.53	37.13	116.53	41.38	-26.29	175.01	-40.86	44.57	12.50	39.69	-157.07
174.68	-41.42	31.32	153.90	84.87	-27.02	176.44	-40.63	26.19	216.27	68.54	-157.34
174.59	-40.95	57.48	318.23	33.28	-28.38	173.82	-41.50	52.80	148.49	41.12	-158.14
174.82	-40.55	72.68	155.53	79.30	-28.75	175.15	-40.40	20.81	332.35	74.88	-158.82
174.88	-40.82	31.78	347.04	36.63	-29.59	174.70	-40.47	16.37	198.50	59.98	-159.06
175.89	-40.57	33.24	113.63	76.36	-29.89	175.73	-40.88	30.04	196.57	73.68	-159.61
175.70	-40.55	37.05	104.73	46.65	-32.40	174.73	-40.98	33.60	4.89	40.39	-160.31
174.79	-41.18	35.90	334.52	63.62	-32.49	176.45	-40.77	25.80	22.00	57.57	-161.02
175.48	-40.51	28.65	117.38	31.05	-33.21	173.97	-40.65	79.66	73.22	48.38	-161.24
175.00	-40.62	28.62	114.85	50.96	-34.17	173.61	-41.34	56.84	50.27	41.41	-162.56
174.71	-41.43	35.83	91.39	86.73	-34.45	176.23	-40.79	27.64	199.78	59.60	-163.76
173.59	-41.11	84.21	290.02	66.36	-35.19	174.32	-40.68	56.38	10.94	6.18	-164.15
174.71	-41.42	34.84	74.12	61.13	-35.43	174.65	-40.98	33.87	174.96	39.80	-164.16
173.80	-41.17	58.30	132.13	52.49	-36.69	176.66	-41.28	40.01	6.02	88.21	-164.66
173.86	-40.97	63.08	305.35	7.99	-36.69	174.22	-40.68	79.55	36.12	8.32	-164.70

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
174.33	-41.29	68.72	316.02	23.04	-36.71	174.47	-40.68	26.06	334.42	83.33	-165.31
175.78	-40.55	32.12	98.39	86.91	-36.98	174.17	-40.61	73.09	183.19	39.20	-165.80
175.96	-40.68	38.83	200.53	26.01	-37.35	174.72	-41.11	37.06	231.90	11.92	-165.87
174.14	-40.68	106.19	88.18	8.05	-37.66	173.99	-41.20	60.21	205.49	55.90	-166.04
174.65	-41.20	34.92	236.79	37.00	-37.85	173.72	-41.48	80.43	280.35	24.80	-167.28
173.50	-41.12	86.92	338.28	87.26	-38.33	175.04	-41.38	41.28	310.08	31.68	-168.20
175.95	-40.63	33.21	112.97	33.17	-38.41	174.96	-40.66	31.24	147.56	37.90	-169.17
174.76	-41.00	30.70	268.44	51.26	-38.82	174.70	-41.42	35.15	60.52	61.89	-169.99
176.19	-40.77	24.15	238.87	32.96	-39.48	173.73	-41.06	70.32	341.08	25.26	-170.40
176.23	-41.37	20.13	343.03	20.80	-39.62	176.53	-40.62	21.63	185.12	50.00	-170.99
174.80	-41.34	46.52	348.00	76.49	-39.72	174.52	-40.65	62.20	317.97	56.67	-171.48
174.61	-41.11	32.04	41.33	36.67	-39.94	174.16	-40.78	60.72	314.55	32.93	-173.13
175.44	-40.57	27.64	304.03	62.23	-40.05	174.71	-40.47	15.31	208.03	66.87	-173.45
176.55	-40.58	28.38	69.96	29.04	-44.44	174.83	-40.95	53.26	325.28	27.39	-173.66
176.18	-41.34	28.28	1.77	61.66	-45.19	173.57	-40.93	89.55	52.16	52.25	-174.50
175.28	-40.90	33.42	99.44	47.52	-45.60	174.75	-40.98	30.97	204.11	15.28	-174.65
174.73	-40.98	36.73	270.72	55.55	-45.85	174.30	-41.03	32.22	316.08	28.68	-176.03
174.29	-40.90	52.21	285.20	78.96	-45.86	173.48	-40.52	170.75	87.42	48.33	-176.42
174.86	-40.95	30.00	151.41	35.20	-45.97	174.49	-41.27	39.58	146.85	81.15	-176.45
175.87	-40.52	27.60	142.47	89.52	-46.11	173.95	-41.16	58.66	214.29	18.82	-176.67
175.72	-40.47	37.04	309.02	67.22	-46.19	174.11	-41.34	34.56	48.05	23.93	-176.88
175.03	-41.03	45.86	68.66	38.26	-46.47	175.55	-40.49	35.40	24.82	24.45	-177.90

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
173.88	-41.01	60.68	300.88	64.50	-46.61	174.44	-40.99	55.81	300.42	42.50	-178.04
174.49	-41.25	78.12	68.39	36.47	-47.06	174.66	-41.04	53.15	44.25	35.76	-178.20
176.10	-40.90	29.71	278.40	47.52	-47.14	174.50	-41.09	31.54	320.03	51.53	-178.61
175.08	-41.00	38.20	122.06	17.03	-47.22	175.38	-40.66	26.78	15.03	87.38	-178.64
175.09	-40.69	32.10	83.18	44.23	-47.50	175.99	-40.70	33.23	308.84	15.43	-178.88
175.15	-40.85	27.86	109.92	28.32	-47.72	174.48	-40.64	32.39	335.77	81.44	-179.03
175.16	-40.89	32.71	78.09	35.31	-48.04	174.68	-41.42	33.60	161.43	81.86	-179.59
176.20	-41.33	27.98	251.97	40.27	-48.05	173.60	-41.52	60.55	198.77	64.77	179.54
173.59	-41.22	78.27	335.46	70.90	-48.31	174.15	-40.59	102.60	153.76	85.74	179.08
175.67	-40.63	31.68	160.24	62.77	-48.55	175.27	-41.29	33.61	0.33	85.37	178.65
173.74	-41.41	87.38	271.58	52.29	-49.01	174.70	-41.44	35.53	352.32	80.84	178.47
173.86	-41.03	67.32	193.77	43.30	-49.08	173.99	-41.12	60.45	65.35	51.84	178.11
175.08	-40.94	30.66	250.06	39.03	-49.26	175.50	-40.49	28.40	49.35	53.74	177.98
174.59	-40.95	48.60	353.14	30.57	-49.31	173.67	-41.43	51.93	20.95	83.84	177.80
176.05	-40.63	31.68	29.19	25.57	-49.48	173.79	-40.83	84.51	324.42	45.03	176.79
175.23	-40.77	32.27	101.01	59.87	-49.87	174.24	-41.37	37.00	150.85	44.10	176.74
174.95	-40.88	59.01	66.42	37.08	-51.50	175.94	-40.64	28.85	129.04	35.95	176.36
174.55	-40.72	63.59	329.70	77.66	-51.53	175.16	-40.82	31.26	207.38	81.15	176.07
174.15	-40.60	85.82	305.39	4.02	-51.61	173.85	-40.98	60.54	355.69	5.49	175.29
175.90	-40.71	31.21	114.40	23.87	-52.45	175.13	-40.64	34.37	47.45	46.08	175.16
174.74	-40.87	66.39	284.49	52.50	-52.71	174.75	-41.74	43.66	337.80	9.41	175.11
173.69	-41.42	53.60	283.29	43.27	-52.76	174.34	-40.73	81.39	195.36	60.14	174.86

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
174.40	-41.23	62.32	85.39	45.16	-52.83	174.56	-40.67	77.49	76.33	32.05	174.82
174.72	-41.01	30.86	293.92	34.41	-52.93	174.36	-40.74	48.99	239.64	56.07	174.54
174.71	-41.44	36.24	210.24	43.12	-54.36	174.38	-40.51	17.64	181.58	82.79	174.31
174.71	-40.94	33.00	309.27	86.53	-54.55	175.05	-40.53	23.92	150.82	81.51	174.18
174.73	-40.49	27.35	93.43	53.62	-55.13	174.09	-40.71	64.30	0.61	4.20	173.97
175.06	-40.67	35.38	83.41	66.28	-55.93	174.17	-41.08	51.63	168.19	26.91	173.73
173.79	-41.44	52.25	294.45	74.61	-55.95	174.34	-41.40	59.72	222.45	68.63	173.06
176.53	-40.52	26.72	347.86	45.79	-56.83	176.01	-40.90	26.45	174.77	50.77	172.42
173.78	-40.90	111.88	215.67	84.34	-56.84	176.44	-40.60	25.54	120.91	34.00	172.00
174.30	-40.60	50.01	308.22	88.59	-57.12	174.65	-40.90	54.73	343.78	46.11	171.88
174.74	-40.51	23.23	91.70	58.16	-57.15	174.31	-40.65	78.94	328.26	63.10	171.78
174.44	-41.18	62.69	271.89	53.22	-57.39	173.49	-41.22	99.43	84.93	19.12	171.65
174.66	-40.85	66.84	178.95	69.52	-57.73	174.71	-40.48	1.96	34.94	85.90	171.22
175.03	-40.68	28.51	76.54	35.21	-58.07	174.70	-41.43	38.27	330.50	72.77	169.96
174.31	-40.60	98.05	357.61	7.79	-58.44	174.66	-40.92	72.59	22.52	84.09	168.37
174.74	-40.50	21.51	215.70	50.73	-58.80	174.64	-41.21	47.90	348.73	66.56	168.14
174.18	-41.12	60.24	21.34	22.03	-58.97	173.87	-41.14	70.65	274.44	15.77	167.86
174.73	-40.49	22.44	90.41	57.72	-59.33	174.72	-41.27	44.90	344.07	75.27	166.76
176.41	-41.03	33.36	265.06	72.17	-59.88	173.83	-41.40	55.52	21.61	66.14	165.36
175.62	-40.94	32.75	103.88	30.18	-60.49	173.90	-41.35	60.52	17.94	49.25	165.32
175.86	-40.56	23.40	73.55	14.64	-60.68	173.52	-40.71	161.88	122.59	41.49	165.10
176.50	-41.12	26.83	8.74	30.12	-61.98	175.79	-40.56	29.50	115.19	18.64	164.91

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
174.13	-40.86	64.50	125.89	14.21	-62.75	175.69	-40.63	34.31	326.68	15.17	163.85
174.89	-40.92	30.69	241.81	32.68	-63.27	174.56	-41.31	48.20	111.60	35.13	163.20
174.10	-41.09	56.15	74.09	54.22	-63.66	173.87	-41.37	54.73	189.09	19.27	162.39
173.61	-41.10	76.94	334.12	41.59	-64.04	173.88	-41.25	58.33	24.86	30.47	162.05
174.67	-41.06	30.35	249.37	25.49	-64.37	174.76	-41.08	33.33	176.30	65.08	161.92
176.36	-40.67	28.67	72.10	46.85	-65.78	176.34	-40.66	28.12	149.19	88.51	161.72
176.19	-41.32	27.67	217.85	43.41	-65.97	174.72	-41.42	34.61	0.80	89.71	161.50
175.95	-40.58	36.73	167.17	32.61	-67.09	174.35	-40.68	54.43	210.31	70.25	161.46
174.02	-40.53	84.56	320.15	43.50	-68.01	174.88	-41.35	33.43	120.92	42.26	161.10
175.23	-41.23	33.27	24.12	30.86	-68.02	174.41	-40.75	47.71	298.69	72.46	161.00
174.89	-40.92	31.25	248.00	28.33	-68.08	174.52	-40.54	55.11	338.38	63.62	160.41
174.86	-40.47	21.46	51.72	31.50	-68.12	174.56	-40.76	36.80	328.37	80.78	159.28
174.64	-40.52	22.98	263.42	28.20	-68.23	174.57	-40.73	73.45	217.01	24.88	158.92
174.64	-41.22	33.72	55.06	43.19	-69.57	174.71	-40.84	48.10	24.06	70.48	158.52
176.19	-41.32	27.96	229.35	36.09	-69.65	173.82	-41.01	62.38	143.67	53.30	157.83
175.32	-40.76	26.82	294.59	83.32	-69.70	174.42	-40.95	38.94	190.69	89.41	156.43
174.89	-40.91	32.28	245.53	31.38	-69.75	174.52	-40.46	32.75	336.81	41.88	156.36
175.49	-40.57	30.54	259.17	70.25	-69.76	175.92	-40.89	33.43	183.45	87.69	156.32
175.72	-40.61	28.56	290.05	53.55	-69.91	174.87	-41.02	63.74	7.02	53.75	155.19
174.94	-40.71	32.89	198.49	27.48	-70.08	174.45	-41.03	67.51	284.73	34.60	155.00
175.89	-40.61	36.17	100.67	46.97	-70.41	174.67	-40.98	60.19	71.73	26.46	154.75
173.77	-41.32	65.74	291.15	72.04	-70.71	174.14	-41.47	41.60	135.50	42.42	152.90

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
174.89	-40.91	32.66	250.34	37.71	-70.93	174.13	-40.59	99.19	257.36	40.81	152.71
174.70	-41.43	35.26	213.27	42.64	-71.01	173.67	-41.22	68.92	11.99	40.43	152.64
175.61	-40.97	26.25	242.74	88.60	-71.22	174.38	-40.65	74.60	351.40	74.85	152.06
175.28	-40.92	33.09	131.07	58.71	-71.33	175.72	-40.86	25.89	144.88	44.72	151.92
175.92	-40.61	51.86	75.69	52.01	-71.86	173.77	-41.15	76.37	17.28	52.77	151.76
174.02	-41.45	45.66	254.26	56.64	-72.15	173.97	-40.57	97.58	33.06	35.30	151.72
174.73	-40.49	18.40	241.43	48.83	-72.35	174.81	-40.56	56.15	14.41	44.59	151.33
173.59	-40.64	132.10	131.07	47.22	-72.59	174.58	-40.70	69.52	37.21	42.16	150.82
174.90	-40.98	34.11	242.42	45.36	-73.21	174.45	-41.05	59.12	33.26	16.32	148.66
175.51	-40.55	28.23	301.61	61.42	-73.46	173.94	-40.58	111.69	114.49	66.23	148.36
175.41	-40.51	29.08	228.26	26.56	-73.65	174.74	-40.53	54.50	160.59	49.25	147.68
175.08	-40.73	28.20	56.19	46.89	-74.20	174.52	-40.88	80.77	126.00	24.56	146.83
176.20	-40.90	27.90	62.75	60.79	-74.29	174.62	-40.85	60.40	309.31	70.31	146.33
175.05	-40.73	30.85	38.68	23.02	-74.58	174.23	-41.02	52.47	34.37	43.69	146.12
175.93	-40.59	38.31	231.73	59.88	-75.01	173.65	-41.35	86.39	295.40	30.83	145.12
174.73	-40.76	38.62	42.37	43.51	-75.73	173.89	-40.78	133.19	317.09	46.89	145.06
174.63	-40.88	31.57	307.42	65.02	-76.33	173.55	-41.37	75.26	313.73	28.65	143.81
176.12	-40.85	31.80	265.36	28.44	-76.54	174.59	-41.09	38.82	345.99	84.10	142.66
174.73	-41.10	64.02	252.17	70.13	-77.14	174.98	-40.50	26.75	21.25	53.75	142.26
174.75	-40.85	68.27	75.02	56.72	-77.19	173.78	-41.35	48.03	275.62	36.25	141.99
174.48	-41.02	40.74	54.51	58.81	-77.90	173.80	-40.99	85.59	169.36	45.49	141.92
175.74	-40.52	27.16	220.86	74.85	-77.95	176.23	-40.58	28.16	21.57	59.83	141.39

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
176.25	-41.33	22.44	359.81	33.26	-78.62	175.01	-40.73	49.10	31.90	26.48	141.15
174.75	-40.48	23.09	65.62	57.38	-79.32	173.64	-41.42	53.68	356.97	52.12	140.65
176.35	-40.70	27.47	53.69	40.58	-79.86	174.65	-41.07	32.60	37.42	84.80	139.04
175.01	-40.95	33.96	265.86	81.66	-79.98	173.93	-40.50	95.63	30.19	21.15	137.36
174.73	-40.50	21.57	57.44	63.34	-80.14	173.98	-40.68	67.20	234.03	87.24	137.21
176.19	-40.56	26.34	132.92	54.87	-80.24	174.18	-40.70	61.47	44.86	38.19	137.17
173.55	-41.01	116.95	89.61	54.68	-80.40	174.48	-41.02	57.95	279.81	22.61	135.45
175.00	-40.60	27.04	256.18	27.75	-80.79	174.39	-40.71	52.86	149.53	26.30	134.21
176.32	-41.11	25.00	222.51	64.07	-81.44	174.86	-40.58	71.72	359.26	33.22	133.44
174.05	-40.47	55.10	90.74	41.78	-81.49	173.73	-41.42	52.57	162.94	87.69	133.30
174.69	-40.97	58.93	61.08	40.67	-81.95	175.98	-40.55	23.79	164.73	25.11	133.13
176.53	-41.15	26.72	225.14	54.13	-82.22	174.29	-40.58	59.13	106.56	37.72	131.73
176.00	-40.50	31.86	95.48	58.13	-82.55	174.33	-40.62	59.09	155.74	43.43	131.48
176.56	-41.20	39.24	23.01	52.98	-82.72	175.84	-40.60	31.27	150.01	17.64	130.89
175.02	-41.07	31.22	58.55	16.49	-82.84	174.30	-40.49	52.36	245.15	13.28	130.40
175.19	-40.86	29.83	105.03	62.24	-84.30	174.41	-40.50	97.91	11.82	89.69	129.34
175.02	-40.62	26.64	76.02	73.22	-84.92	174.70	-40.69	27.70	2.54	57.32	129.33
176.06	-41.46	38.59	229.69	47.39	-84.92	173.85	-41.19	61.31	223.55	63.24	129.09
174.86	-41.06	31.89	222.90	61.18	-86.12	175.70	-40.96	42.04	190.96	85.74	128.27
175.16	-40.54	41.68	246.30	79.29	-86.22	173.92	-41.50	48.54	86.99	49.32	127.67
175.96	-40.58	33.42	194.20	34.93	-86.36	174.37	-41.38	42.69	88.78	26.31	127.36
174.99	-40.50	25.33	128.58	67.89	-86.38	174.48	-41.06	45.25	355.21	86.12	127.31

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
175.10	-40.76	38.50	76.47	24.72	-87.69	173.48	-41.48	77.06	346.32	49.00	123.09
175.81	-40.56	32.06	264.05	55.84	-87.82	173.51	-41.49	66.75	195.70	37.62	122.01
175.17	-40.94	36.05	251.61	84.63	-88.41	174.31	-40.89	72.89	3.30	18.45	120.72
174.71	-40.47	2.87	70.64	83.52	-89.02	173.58	-40.78	152.95	291.29	66.27	120.45
176.41	-40.67	24.19	208.70	55.88	-89.13	174.61	-41.39	58.74	187.01	64.44	120.37
175.69	-40.56	30.62	235.62	26.12	-89.25	173.87	-41.02	67.04	297.22	5.11	120.34
174.90	-40.91	32.37	67.19	53.60	-89.43	173.98	-41.18	65.80	349.56	42.81	119.99
176.17	-41.29	26.03	18.71	57.35	-89.69	176.19	-40.79	27.29	247.65	13.49	116.70
175.14	-40.81	34.13	238.92	59.40	-90.37	175.97	-40.84	30.40	120.47	4.61	114.26
175.04	-41.05	31.06	211.74	53.61	-90.40	174.23	-40.57	61.85	140.46	53.91	111.54
176.25	-40.87	29.64	136.77	46.26	-91.64	174.58	-40.85	39.55	176.63	38.14	109.32
174.84	-41.07	31.69	58.05	41.34	-92.04	174.61	-40.77	45.69	280.93	58.87	105.83
175.93	-40.50	32.92	133.79	61.10	-92.15	173.58	-40.96	80.22	85.39	63.77	105.51
174.88	-40.91	32.02	34.44	63.03	-93.30	174.37	-40.64	51.42	285.08	69.19	102.77
173.92	-41.49	47.30	94.83	20.34	-93.34	173.75	-40.88	68.79	279.13	11.82	100.38
175.11	-40.87	30.77	55.61	26.77	-93.50	173.73	-41.20	66.90	61.37	79.73	100.03
175.40	-40.44	26.91	289.04	56.67	-93.81	173.71	-40.53	100.78	142.73	13.15	97.90
174.90	-40.93	31.44	23.77	24.70	-94.07	174.04	-41.13	58.09	175.86	40.19	97.59
173.89	-41.17	71.45	300.68	49.17	-94.69	173.64	-41.53	59.72	321.16	58.84	96.91
175.30	-40.60	26.90	8.12	25.57	-94.73	173.82	-41.00	71.33	100.95	75.73	96.50
175.26	-41.48	43.06	276.22	88.21	-95.35	175.98	-40.62	28.35	320.56	86.31	95.42
176.34	-40.71	30.00	202.12	47.15	-95.37	174.11	-41.24	53.34	63.78	54.16	91.96

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
175.08	-40.67	38.32	359.30	34.06	-95.39	173.99	-41.40	42.10	300.26	21.92	90.49
175.91	-40.51	34.73	76.35	73.26	-95.68	174.96	-41.07	34.64	209.35	5.69	90.14
174.97	-40.94	30.72	49.02	43.14	-95.69	174.15	-41.14	47.27	262.41	7.44	89.66
175.43	-40.58	25.10	147.07	24.87	-96.09	174.00	-41.23	57.73	260.24	6.41	89.46
174.80	-41.29	49.39	82.39	39.96	-96.50	174.06	-41.00	57.42	58.72	63.51	88.33
174.10	-41.33	40.75	294.86	53.87	-96.67	173.57	-41.18	77.88	221.89	25.48	86.12
174.52	-41.22	35.31	45.35	35.03	-96.80	173.81	-41.39	63.59	53.56	63.00	86.03
175.08	-40.93	37.08	243.95	74.76	-96.90	174.41	-41.04	67.76	65.60	78.20	85.16
175.78	-40.90	28.54	220.07	31.32	-97.06	176.14	-40.62	27.63	25.69	82.40	84.20
174.70	-41.43	32.43	7.32	47.56	-97.94	175.50	-40.58	34.34	269.94	19.97	83.14
174.92	-40.94	31.47	36.39	23.67	-97.96	174.56	-40.97	63.00	96.58	54.56	82.98
175.47	-40.55	28.43	72.50	47.24	-98.12	173.93	-41.37	69.79	192.53	36.91	81.76
174.37	-40.68	79.00	70.48	76.12	-98.38	173.78	-40.58	121.64	260.34	26.19	81.58
173.96	-40.75	63.15	70.16	8.87	-98.71	174.13	-41.29	46.09	156.02	41.64	79.50
175.49	-40.61	27.36	30.72	47.60	-99.10	176.42	-40.50	32.49	173.63	40.58	79.16
176.50	-40.63	27.43	221.68	79.65	-99.21	174.39	-40.71	80.61	42.88	83.11	79.07
176.37	-40.69	26.81	215.83	63.67	-99.85	173.98	-40.71	83.98	174.19	39.68	72.29
174.57	-40.49	37.25	278.94	47.56	-99.92	174.46	-40.88	75.37	250.32	9.01	71.19
176.48	-41.27	36.36	201.95	49.10	-100.48	174.43	-40.98	63.08	29.29	75.14	70.76
175.71	-40.61	31.12	268.77	68.74	-101.05	173.82	-40.63	111.45	204.80	57.65	69.84
173.77	-41.31	60.29	84.71	46.84	-101.59	174.19	-40.76	52.35	64.05	7.19	66.73
175.07	-41.05	32.30	242.23	29.65	-101.60	174.06	-40.72	98.88	91.63	51.69	66.17

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
175.91	-40.57	33.25	249.38	26.13	-101.66	176.07	-40.83	27.95	252.71	85.34	65.48
174.45	-40.65	72.45	239.27	9.00	-101.78	174.43	-40.91	54.22	45.54	85.43	64.56
174.65	-41.43	34.90	5.49	15.86	-102.05	173.63	-40.87	94.63	282.46	7.51	63.86
176.37	-40.93	27.14	12.00	27.80	-102.17	173.64	-41.11	85.95	279.08	89.36	62.21
175.19	-40.88	32.80	220.85	34.07	-102.72	173.52	-40.90	88.73	187.19	14.72	61.69
174.79	-40.99	60.26	221.92	10.21	-102.83	175.09	-40.54	36.26	51.23	84.66	61.57
175.89	-40.56	32.98	258.13	27.35	-103.39	173.64	-41.25	88.17	101.90	35.19	61.43
175.02	-41.16	33.70	246.61	74.05	-104.35	174.03	-41.32	45.89	359.87	36.06	60.99
175.30	-40.70	35.49	235.78	57.92	-104.39	174.67	-40.96	42.93	197.86	15.37	60.35
175.60	-40.96	29.70	61.54	40.45	-104.48	174.01	-40.89	76.80	205.85	3.16	60.26
174.33	-40.67	59.45	263.01	64.21	-104.72	173.92	-41.30	57.54	172.03	26.18	58.48
174.36	-41.22	73.37	344.03	9.32	-105.01	173.92	-40.93	74.28	94.73	61.52	57.37
174.60	-41.15	43.91	35.40	42.45	-105.67	173.57	-40.50	158.11	77.95	72.83	53.03
173.81	-41.09	63.23	108.83	29.61	-106.36	174.53	-41.27	36.61	27.30	50.27	51.40
174.36	-40.70	15.47	40.39	38.47	-106.44	174.38	-40.53	91.47	21.16	64.10	49.98
176.21	-40.75	29.08	30.39	60.25	-106.56	174.52	-41.00	62.71	264.67	15.40	49.87
175.10	-40.75	31.50	234.15	47.91	-106.63	174.27	-41.14	63.91	65.56	32.94	49.38
175.75	-40.82	27.42	310.46	28.65	-106.81	173.81	-41.25	59.58	140.14	26.37	49.35
176.18	-40.54	29.11	251.70	45.88	-106.94	174.74	-40.49	55.00	158.84	38.72	48.25
174.74	-40.49	28.85	224.30	55.19	-107.41	173.89	-40.93	79.96	161.54	25.21	48.09
175.71	-40.58	55.37	254.62	25.03	-107.82	174.15	-41.36	38.97	288.62	88.06	47.95
174.45	-40.93	54.40	114.49	52.09	-107.97	174.28	-41.51	72.31	359.88	34.10	47.56

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
175.01	-40.80	37.44	52.16	36.94	-108.23	174.59	-40.86	36.71	348.71	19.72	46.58
174.87	-40.75	41.08	81.93	37.93	-108.70	174.40	-41.01	49.33	23.59	35.54	46.33
174.83	-40.54	24.56	64.47	29.99	-108.70	174.60	-41.40	49.03	140.70	42.48	43.38
174.52	-41.39	30.18	54.96	81.55	-108.79	173.82	-41.00	75.60	358.85	85.05	40.14
175.00	-40.91	29.29	270.25	51.78	-108.92	173.98	-40.92	72.03	49.56	49.64	35.82
174.75	-41.08	32.53	222.24	51.49	-109.07	174.00	-41.38	69.23	211.06	49.78	35.42
174.81	-41.25	32.69	36.37	19.96	-110.49	174.58	-40.72	50.01	134.68	21.41	34.75
174.76	-41.08	63.20	54.31	17.09	-111.42	174.71	-40.83	85.19	18.44	40.46	34.27
175.29	-40.74	26.61	88.75	22.57	-111.49	174.67	-41.42	32.84	256.45	66.37	33.66
176.05	-40.62	31.80	99.80	22.17	-111.84	175.84	-40.51	27.29	89.15	73.35	33.26
174.69	-40.95	59.75	58.50	78.35	-112.08	173.72	-41.00	96.18	48.35	18.96	32.24
175.30	-40.50	30.69	47.86	54.48	-113.85	173.80	-41.33	53.87	177.69	38.06	31.46
176.08	-40.86	28.56	43.57	48.29	-114.28	173.68	-41.19	63.00	86.21	31.40	30.45
174.98	-41.28	30.24	18.51	25.40	-114.62	174.13	-40.63	76.78	354.03	55.30	30.12
176.39	-40.71	24.56	32.72	54.60	-115.30	175.91	-40.49	36.37	21.83	78.75	29.84
175.96	-40.52	31.98	229.75	62.42	-116.51	175.22	-40.62	25.00	173.64	52.81	27.99
173.67	-40.69	98.93	246.47	8.52	-117.60	174.43	-40.71	71.88	275.53	76.70	27.71
176.26	-41.41	24.28	21.60	39.17	-117.89	176.11	-40.88	33.04	16.84	34.37	26.42
173.65	-40.90	83.97	250.41	18.63	-118.09	173.86	-41.29	57.94	40.50	77.94	24.08
174.67	-41.07	30.41	49.19	80.00	-118.16	174.85	-40.62	38.47	309.60	43.92	23.59
173.75	-40.45	103.02	59.85	16.86	-118.89	174.18	-41.34	38.00	218.87	13.32	23.30
175.84	-40.54	34.12	83.74	44.56	-119.14	174.70	-40.97	34.93	49.45	31.22	23.20

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
174.85	-40.91	31.99	40.38	39.19	-119.14	173.79	-41.32	54.27	27.04	43.68	22.89
174.89	-40.91	33.07	40.27	48.76	-119.39	175.69	-40.56	46.43	229.09	19.74	22.42
174.20	-40.47	55.00	32.14	26.70	-119.61	173.83	-41.01	76.64	42.54	42.30	22.27
175.45	-40.55	26.11	36.59	46.00	-119.80	174.44	-41.07	72.90	104.81	71.67	21.85
175.05	-40.73	32.48	216.04	37.18	-120.15	174.70	-41.03	56.88	86.42	78.24	21.50
173.88	-40.66	62.81	247.72	26.14	-120.17	173.74	-41.39	61.08	36.09	52.04	21.27
175.02	-40.78	36.25	207.51	72.08	-121.03	174.97	-40.94	79.40	33.04	76.65	20.30
175.04	-41.05	31.33	209.29	44.72	-121.23	174.40	-40.55	14.11	200.01	59.82	19.92
174.56	-41.15	57.36	42.81	63.55	-121.52	174.27	-40.99	79.52	290.37	13.92	19.09
174.72	-41.40	33.85	29.41	67.34	-121.59	174.48	-40.79	78.08	76.44	27.91	18.30
175.27	-40.98	49.65	200.02	73.31	-122.38	173.81	-41.07	59.54	358.51	16.02	18.28
174.41	-41.09	63.11	179.19	68.03	-122.65	174.66	-40.97	38.75	9.17	66.11	18.28
175.87	-40.57	34.99	241.17	34.26	-123.73	174.72	-41.44	38.91	92.13	60.81	18.10
175.12	-40.50	28.02	180.96	76.24	-123.95	176.11	-40.57	32.69	20.96	32.71	16.57
175.04	-41.06	29.46	20.03	18.39	-124.17	174.40	-41.01	47.01	159.37	65.83	16.54
174.74	-40.47	29.61	221.38	51.14	-124.36	174.34	-40.66	88.99	32.81	70.62	16.37
173.59	-40.92	105.29	3.47	34.02	-124.38	175.01	-40.95	45.52	326.80	17.90	15.39
175.45	-40.60	26.57	86.14	42.91	-124.89	174.65	-40.62	81.19	153.55	8.92	13.65
175.03	-40.80	36.03	216.14	58.38	-124.94	174.72	-40.94	55.49	1.17	34.27	12.64
173.80	-40.59	109.80	190.80	70.83	-125.15	174.37	-40.60	86.89	344.05	48.43	12.41
175.12	-40.78	38.37	215.80	34.71	-126.26	174.63	-40.85	62.66	7.92	64.18	11.43
173.65	-40.63	117.20	301.20	5.57	-126.70	174.06	-40.56	105.00	92.46	37.76	11.37

Table 9.2 continued from previous page

Longitude	Latitude	Depth	Strike	Dip	Rake	Longitude	Latitude	Depth	Strike	Dip	Rake
175.99	-40.72	27.40	250.37	29.02	-127.04	174.55	-41.26	69.18	22.43	67.68	11.16
174.47	-41.32	54.07	14.77	31.24	-127.12	173.75	-40.92	60.01	331.04	28.95	11.14
174.74	-40.50	26.76	223.81	46.83	-127.25	174.41	-40.74	80.34	77.81	39.84	10.50
174.65	-40.49	24.18	220.93	42.17	-127.38	174.79	-41.01	34.11	20.37	45.15	10.16
174.47	-40.94	47.91	332.98	19.36	-128.09	175.46	-40.53	28.60	208.66	59.97	10.10
174.46	-41.10	38.09	21.99	27.79	-128.28	174.20	-41.32	38.85	202.47	65.10	9.90
174.98	-41.11	33.49	0.67	24.24	-128.34	174.06	-40.50	102.04	177.41	15.16	9.39
174.64	-41.10	62.50	15.55	60.45	-128.46	174.29	-41.09	77.20	323.71	12.48	8.74
174.73	-40.49	26.72	221.38	49.31	-128.51	174.26	-40.69	53.19	45.38	57.41	8.61
174.51	-41.23	37.37	287.16	39.26	-128.69	174.22	-40.81	57.44	30.69	81.55	8.59
174.97	-40.75	36.68	185.43	31.72	-129.72	174.43	-40.93	76.47	15.33	67.43	8.51
176.12	-40.89	34.47	204.23	33.70	-130.54	174.65	-41.11	30.80	99.71	24.01	6.33
175.08	-40.77	35.00	211.90	33.47	-130.89	174.95	-40.83	64.37	315.15	30.16	6.19
174.55	-41.23	41.41	202.16	72.35	-131.05	175.97	-40.50	24.45	329.74	37.24	5.12
174.73	-40.49	17.16	208.95	34.22	-131.09	174.42	-41.03	46.76	329.06	62.18	3.23
175.06	-40.51	40.75	266.41	27.15	-132.08	174.38	-41.37	56.05	10.85	69.73	2.07
174.39	-41.27	63.55	307.84	16.80	-132.36	173.56	-41.51	71.47	281.51	51.46	1.87
174.74	-40.77	37.92	40.20	57.68	-132.67	175.13	-40.81	29.74	34.18	64.27	1.30
175.46	-41.33	36.38	109.52	17.53	-132.88	175.71	-40.89	27.96	282.81	55.90	0.80
174.64	-40.53	28.40	16.96	45.63	-133.67	174.49	-40.93	73.78	65.14	18.70	0.79
175.84	-40.51	31.56	353.34	13.87	-133.77	174.63	-40.77	76.13	70.04	31.93	0.07
173.50	-41.26	73.75	92.51	49.17	-133.85						

Table 9.3: Results of stress inversion for the down-dip lower plane of the Double Benioff Zone (focal mechanisms with 10 or more polarity picks). Mean and Medium values calculated using the Bayesian method. X10 and X90 indicate the 80% confidence interval bounds. Map indicated parameters calculated using the Map method, embedded in the Bayesian program (for comparisons only).

Parameter	Mean	Map	Median	X10	X90
S1	43.01	41.54	42.15	17.32	69.94
S2	138.40	135.00	-42.66	-71.58	-10.54
S3	93.09	100.38	-90.84	-147.49	-1.39
SHmax	39.95	43.20	38.92	11.10	70.27
Nu	0.38	0.40	0.38	0.20	0.56

Table 9.4: Results of stress inversion for the up-dip lower plane of the Double Benioff Zone (focal mechanisms with 10 or more polarity picks). Mean and Medium values calculated using the Bayesian method. X10 and X90 indicate the 80% confidence interval bounds. Map indicated parameters calculated using the Map method, embedded in the Bayesian program (for comparisons only).

Parameter	Mean	Map	Median	X10	X90
S1	47.87	48.46	47.62	00.85	97.27
S2	54.07	51.92	53.17	20.09	90.63
S3	141.38	138.46	-39.40	-61.56	-15.13
SHmax	49.60	50.40	49.14	28.00	71.33
Nu	0.24	0.00	0.19	-0.02	0.60

Table 9.5: Results of stress inversion for the upper plane of the Double Benioff Zone (focal mechanisms with 10 or more polarity picks). Mean and Medium values calculated using the Bayesian method. X10 and X90 indicate the 80% confidence interval bounds. Map indicated parameters calculated using the Map method, embedded in the Bayesian program (for comparisons only).

Parameter	Mean	Map	Median	X10	X90
S1	145.65	148.85	-34.31	-75.38	6.62
S2	61.17	62.31	61.29	46.99	75.24
S3	149.71	148.85	-30.26	-42.07	-18.70
SHmax	59.66	61.20	59.71	47.03	71.68
Nu	0.50	0.50	0.50	0.38	0.61

Figure 9.1: A comparison of this study's region of interest (cyan) and McGinty et al. (2000) study area (magenta). This study uses a maximum of 434 and 225 focal mechanisms in the inversion of stresses in the upper and lower bands of seismicity, respectively. Cyan shaded region indicates where bending stresses are observed based on this study. McGinty et al. (2000) used 48 and 12 focal mechanisms in the inversion of stresses in the upper and lower bands of seismicity, respectively, observing no bending stresses. Dashed-lines indicate plate interface depth (Williams et al., 2013). Grey lines show active faults (<https://data.gns.cri.nz/af/>).

Figure 9.2: A comparison of the radius of curvature for the southern North Island (b, cyan) and the northern South Island (a, magenta), based on plate interface depth (see Figure 4.5, Chapter 4). Calculating radius of curvature (R) between depths of 40 and 100 km along the plate interface, where we observed bending stresses. $R = (AB/2) + (2BC)^2/(8AB)$. Radius of curvature in the southern North Island is 149 km and 225 km in the northern South Island. Plate interface depth based on Williams et al. (2013).

Figure 9.3: Clusters of all focal mechanisms used as inputs into the Bayesian stress inversion method from Arnold and Townend (2007). Red-dashed line indicates approximate of the Moho (Henry et al., 2013). Upper cluster (434 focal mechanisms) shown by cyan circles, down-dip lower (left) cluster shown by magenta circles (132 focal mechanism) and up-dip lower (right) cluster shown by orange circles (93 focal mechanism), mapped on X to X' cross-section from previous figures. Stereonets show azimuth of maximum principle stress (S1), intermediate principle stress (S2), and minimum principle stress (S3), shown as the posterior density functions (PDFs). The best fitting maximum horizontal stress (SHmax) shown as a dashed line. Black arrows indicate plate convergence direction.

Table 9.6: Results of stress inversion for the down-dip lower plane of the Double Benioff Zone (all focal mechanisms). Mean and Medium values calculated using the Bayesian method. X10 and X90 indicate the 80% confidence interval bounds. Map indicated parameters calculated using the Map method, embedded in the Bayesian program (for comparisons only).

Parameter	Mean	Map	Median	X10	X90
S1	81.62	76.15	81.84	42.47	121.11
S2	174.08	166.15	-05.77	-41.28	30.23
S3	108.82	117.69	-68.56	-113.11	-37.20
SHmax	70.16	48.56	66.40	24.13	121.00
Nu	0.26	0.20	0.25	0.12	0.42

Table 9.7: Results of stress inversion for the up-dip lower plane of the Double Benioff Zone (all focal mechanisms). Mean and Medium values calculated using the Bayesian method. X10 and X90 indicate the 80% confidence interval bounds. Map indicated parameters calculated using the Map method, embedded in the Bayesian program (for comparisons only).

Parameter	Mean	Map	Median	X10	X90
S1	40.60	41.54	41.32	10.71	66.90
S2	52.49	51.92	51.97	34.44	71.57
S3	139.39	138.46	-40.74	-55.53	-25.66
SHmax	48.86	50.81	48.79	35.76	61.46
Nu	0.16	0.20	0.13	-0.03	0.36

Table 9.8: Results of stress inversion for the upper plane of the Double Benioff Zone (all focal mechanisms). Mean and Medium values calculated using the Bayesian method. X10 and X90 indicate the 80% confidence interval bounds. Map indicated parameters calculated using the Map method, embedded in the Bayesian program (for comparisons only).

Parameter	Mean	Map	Median	X10	X90
S1	150.03	159.23	-28.68	-64.17	00.79
S2	59.55	62.31	60.17	45.14	72.96
S3	144.06	145.38	-35.95	-46.08	-25.95
SHmax	53.86	56.70	53.72	42.80	64.28
Nu	0.45	0.40	0.45	0.37	0.53

Figure 9.4: Comparison of HypoDD (green), NonLinLoc (cyan), and SEISAN Hypocenter (magenta) earthquake locations. Map-view shows little variation between the three location programs, whereas cross-section show variability. HypoDD locations calculated using 1D velocity model from Eberhart-Phillips and Reyners (1997) to make comparison to Du et al. (2004). NonLinLoc, as previously stated is made using 3D velocity model from Eberhart-Phillips et al. (2010). SEISAN Hypocenter locations calculated using 1D velocity model adapted from Henrys et al. (2013). Variation in cross-sectional view indicates that locations are highly dependent on velocity model. NonLinLoc location display most recognizable double Benioff zone. HypoDD was able to discern between two bands of seismicity in the upper portion of the subduction zone, but fail to in deeper reaches, due to amount of seismicity. HypoDD relies on a large-dense earthquake catalog, thus these findings are not unexpected. Using SEISAN Hypocenter location a double Benioff zone is unrecognizable.

Figure 9.5: Stress inversions of clusters of focal mechanisms based on HypoDD and SEISAN locations. For cluster boundaries see Figure 9.3. All focal mechanisms used as inputs into the Bayesian stress inversion method from Arnold and Townend (2007). Stereonets show azimuth of maximum principle stress (S1, red), intermediate principle stress (S2, green), and minimum principle stress (S3, blue), shown as the posterior density functions (PDFs). Stress inversions using all location programs show similar results : extension in the upper band, compression in the down-dip lower band, and extension in the up-dip lower band. The best fitting maximum horizontal stress (SHmax) shown as a dashed line.

Figure 9.6: Clusters of focal mechanisms based on NonLinLoc locations. Clusters boundaries defined by those in the upper and lower bands of seismicity. Upper cross-sections show clusters with 10 or more polarity picks. Lower cross-section consists of focal mechanism regardless of number of polarity picks.

Figure 9.7: Stress inversions of 2 clusters of focal mechanisms. Stereonets show azimuth of maximum principle stress (S1, red), intermediate principle stress (S2, green), and minimum principle stress (S3, blue), shown as the posterior density functions (PDFs). Stress inversions using all location programs show similar results : extension in the upper band and lower band of seismicity. This indicates that bending stress are being overprinted by down-dip tension.

Chapter 10

Appendix C: Stress and Structure Controlled Anisotropy Revealed by a High-Density Seismic Transect Across Southern North Island, New Zealand

This chapter provides appendix material for Chapter 5: *Crustal Anisotropy Across Southern North Island, New Zealand Revealed by a High Density Seismic Array*. Figures show average unstacked fast azimuth and splitting parameters using splitting results from the all unstacked earthquakes, five random earthquakes, the four closest earthquakes to the SAHKE II array, and one earthquake. In addition are tables that include fast azimuth and delay time statistics.

Figure 10.1: Location of 291 high frequency seismic stations (Green circles - appears as Green line). 21 earthquakes (red, white, and blue circles) colored by depth. Dashed-black lines show plate interface depth (Williams et al., 2013). Thick-black lines and grey lines show active faults (e.g., Wellington and Wairarapa faults). Map-inset: New Zealand tectonics showing location of plate boundaries (Red-dashed lines): Alpine Fault, Hikurangi Margin (HK), and North Island Seismic Belt (NISB) (Coffin et al., 2008). Black box indicates location of study area.

Figure 10.2: Fast azimuth (degrees from North) measurements from all unstacked earthquakes as a function of distance along the SAHKE II array. Distance 0 km indicates location of westernmost seismic station. Black dot are fast azimuth measurements. Oranges, yellows and greens indicate increase density of measurements. Red-line is the 50-point moving average. Dashed-grey lines separate difference regions of interest (from West-East, see Figure S1): West-coast to the Wellington fault, Wellington fault to the Wairarapa fault, the Wairarapa Basin, and Dry Creek fault to East-coast. Solid-white lines mark the average fast azimuth, dashed-white lines show the 95% confidence intervals.

Figure 10.3: Mean fast azimuth for each seismic station. Colors (e.g., green, tan, red, blue) indicate grouping of mean azimuths for averaging. Boundaries defined in previous figures. Colored numbers and yellow wedges indicate the mean fast azimuth and 95% confidence interval, respectfully.

Figure 10.4: Density plots comparing various attributes of all A and B splitting measurements made using MFAST. Measurement attributes compared are: angle of incidence, back azimuth, delay time, distance (earthquake - station), and fast direction azimuth. Hotter colors (reds) indicated a higher occurrence. No one attribute shows a strong dependence on any other, indicating a singular source for the anisotropy measurements calculated.

Figure 10.5: MFAST filters used in splitting calculation of all A and B splitting measurements. Lower frequency (0.2 - 5 Hz) filters gave more high quality (A & B quality) measurements.

Figure 10.6: Location of 291 high frequency seismic stations (Green circles - appears as Green line). The four closest earthquakes, colored by depth, to the SAHKE II array. For all other features see Figure S1.

Figure 10.7: Fast azimuth (degrees from North) measurements from the four closest earthquakes to the SAHKE II array as a function of distance along the SAHKE II array. Red line is the 40-point moving average. For all other features see Figure S2.

Figure 10.8: Mean fast azimuth for each seismic station using the four closest earthquakes. Colors (e.g., green, tan, red, blue) indicate grouping of mean azimuths for averaging. For all features see Figure S3.

Figure 10.9: Density plots comparing various attributes of the A and B splitting measurements made using MFAST from the four closest earthquakes. Measurement attributes compared are: angle of incidence, back azimuth, delay time, distance (earthquake - station), and fast direction azimuth. No one attribute shows a strong dependence on any other, indicating a singular source for the anisotropy measurements calculated. For all other features see Figure S4.

Figure 10.10: MFAST filters used in splitting calculation of the A and B splitting measurements from the four closest earthquakes. Lower frequency (0.2 - 5 Hz) filters gave more high quality (A & B quality) measurements.

Figure 10.11: Location of 291 high frequency seismic stations (Green circles - appears as Green line) and five randomly chosen earthquakes, colored by depth. For all other features see Figure S1.

Figure 10.12: Fast azimuth (degrees from North) measurements from the four closest earthquakes to the SAHKE II array as a function of distance along the SAHKE II array. Red line is the 25-point moving average. For all other features see Figure S2.

Figure 10.13: Mean fast azimuth for each seismic station using the five randomly chosen earthquakes. Colors (e.g., green, tan, red, blue) indicate grouping of mean azimuths for averaging. For all features see Figure S3.

Figure 10.14: Density plots comparing various attributes of the A and B splitting measurements made using MFAST from the five randomly chosen earthquakes. Measurement attributes compared are: angle of incidence, back azimuth, delay time, distance (earthquake - station), and fast direction azimuth. No one attribute shows a strong dependence on any other, indicating a singular source for the anisotropy measurements calculated. For all other features see Figure S4.

Figure 10.15: MFAST filters used in splitting calculation of the A and B splitting measurements from the five randomly chosen earthquakes. Lower frequency (0.2 - 5 Hz) filters gave more high quality (A & B quality) measurements.

Figure 10.16: Location of 291 high frequency seismic stations (Green circles appears as Green line) and a single earthquake, colored by depth, with lots measurements. For all other features see Figure S1.

Figure 10.17: Fast azimuth (degrees from North) measurements from a single earthquake source as a function of distance along the SAHKE II array. Red line is the 20-point moving average. For all other features see Figure S2.

Figure 10.18: Mean fast azimuth for each seismic station using a single earthquake source. Colors (e.g., green, tan, red, blue) indicate grouping of mean azimuths for averaging. For all features see Figure S3.

Figure 10.19: Density plots comparing various attributes of the A and B splitting measurements made using MFAST from a single earthquake source. Measurement attributes compared are: angle of incidence, back azimuth, delay time, distance (earthquake - station), and fast direction azimuth. No one attribute shows a strong dependence on any other, indicating a singular source for the anisotropy measurements calculated. For all other features see Figure S4.

Figure 10.20: MFAST filters used in splitting calculation of the A and B splitting measurements from a single earthquake source. Lower frequency (0.2 - 5 Hz) filters gave more high quality (A & B quality) measurements.

Region	Stations	# of Meas.	Fast Az.	95% CI	Delay Time (s)	95% CI
West of Well.	01-55	296	21.07	5.51	0.165	0.014
Well. - Wair.	56-144	430	46.27	5.14	0.19	0.013
Wair. - DC.	145-211	258	0.32	6.22	0.212	0.019
East of DC.	212-291	272	29.54	6.5	0.215	0.018
All Regions	291	1256	28.78	2.9	0.194	0.008

Table 10.1: Fast azimuth (degrees from North) and delay times (seconds), as well as, 95% confidence intervals for all A and B measurements made with MFAST using all earthquakes, see Figure S1. Note: Well. = Wellington fault, Wair. = Wairarapa fault, DC. = Dry Creek fault.

Region	Stations	# of Meas.	Fast Az.	95% CI	Delay Time (s)	95% CI
West of Well.	01-55	71	20.43	10.39	0.144	0.021
Well. - Wair.	56-144	148	49.56	8.57	0.148	0.018
Wair. - DC.	145-211	113	2.62	9.34	0.158	0.024
East of DC.	212-291	152	31.94	8.15	0.186	0.022
All Regions	291	484	31.84	4.53	0.162	0.011

Table 10.2: Fast azimuth (degrees from North) and delay times (seconds), as well as, 95% confidence intervals for all A and B measurements made with MFAST using all earthquakes, see Figure S1. Note: Well. = Wellington fault, Wair. = Wairarapa fault, DC. = Dry Creek fault.

Region	Stations	# of Meas.	Fast Az.	95% CI	Delay Time (s)	95% CI
West of Well.	01-55	50	9.17	13.56	0.18	0.032
Well. Wair.	56-144	111	50.45	9.86	0.225	0.028
Wair. DC.	145-211	31	-2.27	16.38	0.258	0.051
East of DC.	212-291	66	18.91	12.42	0.247	0.049
All Regions	291	258	14.86	6.24	0.227	0.018

Table 10.3: Fast azimuth (degrees from North) and delay times (seconds), as well as, 95% confidence intervals for all A and B measurements made with MFAST using all earthquakes, see Figure S1. Note: Well. = Wellington fault, Wair. = Wairarapa fault, DC. = Dry Creek fault.

Region	Stations	# of Meas.	Fast Az.	95% CI	Delay Time (s)	95% CI
West of Well.	01-55	30	23.45	14.93	0.124	0.023
Well. - Wair.	56-144	59	54.14	13.63	0.142	0.026
Wair. - DC.	145-211	41	-30.31	17.56	0.111	0.021
East of DC.	212-291	42	19.72	16.07	0.176	0.042
All Regions	291	172	33.31	7.74	0.14	0.015

Table 10.4: Fast azimuth (degrees from North) and delay times (seconds), as well as, 95% confidence intervals for all A and B measurements made with MFAST using all earthquakes, see Figure S1. Note: Well. = Wellington fault, Wair. = Wairarapa fault, DC. = Dry Creek fault.

Figure 10.21: Location of 291 high frequency seismic stations (Green circles appears as Green line) and a single earthquake, colored by depth, with lots measurements. For all other features see Figure S1.

Figure 10.22: Fast azimuth (degrees from North) measurements from 2 deep earthquake source as a function of distance along the SAHKE II array. Red line is the 45-point moving average. For all other features see Figure S2. Possible indication of path affects of shear-wave splitting, but few measurements and large confidence intervals.

Figure 10.23: Density plots comparing various attributes of the A and B splitting measurements made using MFAST from two deep earthquakes source. Measurement attributes compared are: angle of incidence, back azimuth, delay time, distance (earthquake - station), and fast direction azimuth. No one attribute shows a strong dependence on any other, indicating a singular source for the anisotropy measurements calculated. For all other features see Figure S4.

Figure 10.24: MFAST filters used in splitting calculation of the A and B splitting measurements from a single earthquake source. Lower frequency (0.2 - 5 Hz) filters gave more high quality (A & B quality) measurements.

Figure 10.25: Rose diagram of the azimuths of bedding planes throughout the Rakaia Terrane (Begg et al., 2000; Heron).

Figure 10.26: Rose diagram of the azimuths of foliation throughout the Rakaia Terrane (Begg et al., 2000; Heron).

Figure 10.27: Rose diagram of the azimuths of bedding planes of the Rakaia Terrane near the SAHKE II array (Begg et al., 2000; Heron).

Figure 10.28: Rose diagram of the azimuths of bedding planes throughout the Pahau Terrane (Begg et al., 2000; Heron).

Figure 10.29: Rose diagram of the azimuths of bedding planes of the Pahau Terrane near the SAHKE II array (Begg et al., 2000; Heron).

Chapter 11

Appendix D: Preliminary Examination of Long-Term and Short-Term Strain Rates in Central New Zealand

This chapter provides appendix material for Chapter 6: *cGPS Strain Parameters in the Southern North and Northern South Island of New Zealand*. Description of Content: Two tables that list the cGPS station velocities for dataset that include and exclude SSEs in both the ITRF2008 and Australian reference frame. A third table gives cGPS velocities averaged over the five days after the $M_W 7.8$ Kairakoura earthquake.

Table 11.1: Time periods for longterm cGPS station parameter calculations

Station	Network	Longitude	Latitude	Start (yyyy-mm-dd)	End (yyyy-mm-dd)	Duration (days)
AKTO	GeoNet	176.46	-40.54	2008-08-01	2011-05-31	1032
AVLN	GeoNet	174.93	-41.20	2006-02-24	2016-03-14	3666
BIRF	GeoNet	176.25	-40.68	2005-01-27	2016-03-14	3973
BTHL	GeoNet	175.14	-41.34	2009-01-12	2016-03-14	2598
CAST	GeoNet	176.20	-40.91	2006-05-14	2009-07-13	1150
CLIM	GeoNet	175.15	-41.14	2005-10-19	2016-03-14	3786
CMBL	GeoNet	174.21	-41.75	2004-01-28	2012-05-03	2999
DNVK	LINZ	176.17	-40.30	2002-10-10	2016-03-14	4868
DURV	GeoNet	173.92	-40.80	2005-03-10	2016-03-14	4013
GLDB	LINZ	172.53	-40.83	2004-02-02	2016-04-30	4407
GNBK	GeoNEt	175.24	-40.08	2008-03-24	2016-03-15	2890
GRNG	GeoNEt	175.46	-39.98	2007-06-22	2016-03-14	3167
HOKI	LINZ	170.98	-42.71	2011-07-12	2014-04-07	1000
HOLD	GeoNet	175.52	-40.90	2008-04-20	2012-09-06	1600
KAIK	LINZ	173.53	-42.43	2004-02-01	2016-06-16	4499
KAPT	GeoNet	174.91	-40.86	2004-06-10	2016-03-14	4280
KORO	GeoNet	175.42	-40.41	2007-06-19	2016-03-14	3190
LKTA	LINZ	172.27	-42.78	2004-05-30	2015-05-17	4000
LEVN	GeoNet	175.24	-40.59	2008-07-29	2016-03-14	2776
MAHA	GeoNet	173.79	-41.29	2009-11-17	2016-03-14	2240
MANG	GeoNet	175.57	-40.67	2005-02-12	2016-03-14	4041

Table 11.1 continued from previous page

Station	Network	Longitude	Latitude	Start (yyyy-mm-dd)	End (yyyy-mm-dd)	Duration (days)
MAST	LINZ	175.58	-41.06	2003-01-04	2016-03-14	4764
MNHR	GeoNet	176.22	-40.47	2011-03-03	2016-03-14	1839
MTBL	GeoNet	175.54	-40.18	2008-03-26	2016-03-14	2909
MTQN	GeoNet	175.24	-41.00	2010-02-09	2016-03-14	2222
NLSN	LINZ	173.43	-41.18	2004-02-09	2016-03-14	4403
NRRD	GeoNet	175.76	-40.39	2008-02-16	2016-03-14	2895
NRSW	GeoNet	176.20	-40.11	2011-01-18	2016-03-14	1881
OHIN	GeoNet	175.79	-39.92	2008-09-03	2016-03-14	2745
OKOH	GeoNet	174.06	-41.02	2009-11-17	2016-03-14	2252
OROA	GeoNet	176.68	-40.10	2010-11-08	2016-03-14	1946
OTAK	GeoNet	175.17	-40.82	2007-10-08	2016-03-14	3074
PAEK	GeoNet	174.95	-41.02	2000-04-11	2016-03-14	5782
PALI	GeoNet	175.25	-41.57	2007-03-22	2016-03-14	3271
PARW	GeoNet	175.43	-41.38	2004-07-15	2016-03-14	4209
PAWA	GeoNet	176.86	-40.03	2012-02-10	2016-06-05	1531
PKNO	GeoNet	175.18	-39.80	2011-03-03	2016-03-14	1837
PNUI	GeoNet	176.20	-39.92	2006-06-30	2016-03-14	3480
PORA	GeoNet	176.64	-40.27	2006-03-25	2016-03-14	3640
PTOI	GeoNet	176.00	-40.60	2006-03-22	2016-03-14	3604
RDLV	GeoNet	175.40	-41.19	2009-01-13	2016-03-14	2615
TAKP	GeoNet	175.96	-40.06	2004-01-31	2016-03-14	4322

Table 11.1 continued from previous page

Station	Network	Longitude	Latitude	Start (yyyy-mm-dd)	End (yyyy-mm-dd)	Duration (days)
TEMA	GeoNet	175.89	-41.11	2007-03-18	2016-03-14	3279
TINT	GeoNet	175.89	-40.78	2006-04-06	2016-03-14	3625
TKHL	GeoNet	172.96	-41.03	2014-06-19	2016-08-25	799
TORY	GeoNet	174.28	-41.19	2005-04-22	2016-03-14	3933
TRAV	GeoNet	175.69	-41.40	2005-06-23	2016-03-14	3909
TRWH	GeoNet	174.63	-41.28	2010-12-02	2012-12-20	749
TURI	GeoNet	176.38	-40.26	2011-09-01	2016-03-14	1657
WANG	LINZ	174.82	-39.79	2003-04-18	2016-03-14	4701
WEST	LINZ	171.81	-41.74	2004-09-23	2015-05-22	3999
WGTN	LINZ	174.81	-41.32	2001-01-01	2016-03-14	5885
WHVR	GeoNet	175.45	-39.73	2011-09-30	2016-03-14	1609
WITH	GeoNet	173.98	-41.56	2009-11-10	2013-03-01	1199
WPAW	GeoNet	176.54	-39.90	2006-04-21	2016-03-14	3606
WPUK	GeoNet	176.44	-40.06	2006-04-20	2016-03-14	3611

Table 11.2: Time periods used for inter-SSE strain parameter calculations

Station	Network	Longitude	Latitude	Start (yyyy-mm-dd)	End	Start	End	Start	End	Duration (days)
AKTO	GeoNet	176.46	-40.54	2008-08-01	2011-05-31					1032
AVLN	GeoNet	174.93	-41.20	2006-02-24	2007-10-18	2008-11-21	2013-01-01	2014-12-02	2016-03-14	2566
BIRF	GeoNet	176.25	-40.68	2005-01-27	2010-09-11	2012-01-24	2013-09-29	2014-11-03	2016-03-14	2925
BTHL	GeoNet	175.14	-41.34	2009-01-12	2016-03-14					2598
CAST	GeoNet	176.20	-40.91	2006-02-10	2016-03-14					3429
CLIM	GeoNet	175.15	-41.14	2005-10-19	2007-06-13	2008-11-01	2012-12-13	2014-08-05	2016-03-14	2686
CMBL	GeoNet	174.21	-41.75	2005-10-19	2016-03-14					3786
DNVK	LINZ	176.17	-40.30	2002-10-10	2004-11-16	2007-03-27	2010-04-06	2012-09-22	2014-02-04	2349
DURV	GeoNet	173.92	-40.80	2005-03-10	2007-07-12	2008-10-04	2012-04-28	2014-10-16	2016-03-14	2663
GLDB	LINZ	172.53	-40.83	2005-06-17	2007-05-20	2009-03-02	2013-01-08			2100
GNBK	GeoNet	175.24	-40.08	2011-07-07	2013-02-26					600
GRNG	GeoNet	175.46	-39.98	2011-12-03	2013-01-06					400
HOKI	LINZ	170.98	-42.71	2000-01-01	2003-01-16	2006-01-05	2008-03-25	2011-07-12	2016-03-07	3499
HOLD	GeoNet	175.52	-40.90	2008-07-29	2012-09-06	2014-01-21	2016-03-14			2282
KAIK	LINZ	173.53	-42.43	2004-02-01	2016-06-16					4499
KAPT	GeoNet	174.91	-40.86	2004-12-29	2007-03-12	2009-02-12	2012-09-08	2015-06-07	2016-03-14	3082
KORO	GeoNet	175.42	-40.41	2010-03-15	2013-03-19	2014-11-09	2015-07-17			1350
LKTA	LINZ	172.27	-42.78	2004-02-04	2009-08-16	2010-12-29	2016-06-20			1627
LEVN	GeoNet	175.24	-40.59	2009-04-03	2012-09-04	2015-02-25	2016-03-14			3999
MAHA	GeoNet	173.79	-41.29	2010-02-20	2013-01-27	2014-12-28	2016-02-02			1450
MANG	GeoNet	175.57	-40.67	2008-07-20	2013-01-26					1650

Table 11.2 continued from previous page

Station	Network	Longitude	Latitude	Start (yyyy-mm-dd)	End	Start	End	Start	End	Duration (days)
MAST	LINZ	175.58	-41.06	2003-01-04	2016-03-14					4764
MNHR	GeoNet	176.22	-40.47	2012-02-14	2013-08-17					550
MTBL	GeoNet	175.54	-40.18	2008-10-12	2010-02-24					500
MTQN	GeoNet	175.24	-41.00	2010-02-09	2012-12-24	2014-10-07	2016-03-14			1572
NLSN	LINZ	173.43	-41.18	2005-06-24	2007-05-27	2008-10-10	2012-08-14	2014-10-26	2016-03-14	2700
NRRD	GeoNet	175.76	-40.39	2008-07-02	2010-06-04	2012-01-28	2012-11-23	2015-02-03	2015-12-05	1296
NRSW	GeoNet	176.20	-40.11	2011-11-14	2013-12-03					650
OHIN	GeoNet	175.79	-39.92	2011-10-26	2013-04-28					550
OKOH	GeoNet	174.06	-41.02	2009-11-17	2012-10-06	2014-12-16	2016-03-14			1599
OROA	GeoNet	176.68	-40.10	2011-09-04	2012-10-08	2013-08-04	2014-12-17	2015-03-27	2016-03-14	1147
OTAK	GeoNet	175.17	-40.82	2008-08-01	2012-09-11	2014-11-22	2016-03-14			1975
PAEK	GeoNet	174.95	-41.02	2000-04-11	2003-01-23	2003-10-01	2008-01-11	2008-12-26	2012-10-28	2949
PALI	GeoNet	175.25	-41.57	2007-03-22	2012-09-13	2014-01-27	2016-03-14			2881
PARW	GeoNet	175.43	-41.38	2004-07-15	2016-03-14					4209
PAWA	GeoNet	176.86	-40.03	2012-02-10	2012-12-06	2014-01-10	2014-11-06	2015-03-17	2015-08-29	750
PKNO	GeoNet	175.18	-39.80	2011-11-06	2013-05-09					550
PNUI	GeoNet	176.20	-39.92	2006-06-30	2010-03-05	2012-02-07	2014-01-23			1999
PORA	GeoNet	176.64	-40.27	2006-10-10	2011-01-09	2011-09-16	2014-06-12			1550
PTOI	GeoNet	176.00	-40.60	2006-03-22	2013-10-02					2749
RDLV	GeoNet	175.40	-41.19	2009-01-13	2016-03-14					2615
TAKP	GeoNet	175.96	-40.06	2005-12-01	2010-05-15	2011-06-22	2013-12-12			2500

Table 11.2 continued from previous page

Station	Network	Longitude	Latitude	Start (yyyy-mm-dd)	End	Start	End	Start	End	Duration (days)
TEMA	GeoNet	175.89	-41.11	2007-03-18	2016-03-14					3279
TINT	GeoNet	175.89	-40.78	2006-04-06	2013-02-12					2499
TKHL	GeoNet	172.96	-41.03	2014-06-19	2016-08-25					799
TORY	GeoNet	174.28	-41.19	2005-04-21	2007-08-29	2008-11-21	2011-01-31	2015-01-04	2015-11-01	1949
TRAV	GeoNet	175.69	-41.40	2005-06-23	2016-03-14					3909
TRWH	GeoNet	174.63	-41.28	2010-12-02	2012-12-20	2015-01-11	2016-03-14			1176
TURI	GeoNet	176.38	-40.26	2001-09-01	2013-11-07					799
WANG	LINZ	174.82	-39.79	2006-01-12	2009-08-10	2012-02-01	2013-08-05			1850
WEST	LINZ	171.81	-41.74	2005-04-14	2007-06-30	2009-05-30	2012-12-24	2014-05-08	2015-09-22	2600
WGTN	LINZ	174.81	-41.32	2000-01-01	2008-01-08	2008-11-03	2013-03-23	2014-04-27	2016-03-14	4785
WHVR	GeoNet	175.45	-39.73	2001-09-30	2013-08-31					699
WITH	GeoNet	173.98	-41.56	2009-11-10	2013-03-01					1199
WPAW	GeoNet	176.54	-39.90	2006-12-25	2007-07-20	2008-10-15	2009-05-03			800
WPUK	GeoNet	176.44	-40.06	2006-11-04	2010-02-22	2013-02-26	2014-04-02			1600

Table 11.3: cGPS station velocities including and excluding SSEs

Station	Longitude	Latitude	SSE:	SSE:	Inter SSE:	Inter SSE:
			E(mm/yr)	N(mm/yr)	E(mm/yr)	N(mm/yr)
AKTO	176.46	-40.54	-27.01	27.27	-25.11	27.27
AVLN	174.93	-41.20	-21.72	33.73	-25.08	34.09
BIRF	176.25	-40.68	-25.99	29.35	-28.32	29.35
BTHL	175.14	-41.34	-31.17	30.99	-31.17	30.99
CAST	176.20	-40.91	-28.07	29.49	-29.13	29.24
CLIM	175.15	-41.14	-23.94	31.94	-26.28	31.94
CMBL	174.21	-41.75	-24.38	32.59	-24.38	32.59
DNVK	176.17	-40.30	-15.44	28.73	-18.14	31.54
DURV	173.92	-40.80	-5.29	40.81	-9.71	40.81
GLDB	172.53	-40.83	-1.28	42.71	-2.56	42.71
GNBK	175.24	-40.08	-3.91	34.68	-10.99	34.68
GRNG	175.46	-39.98	-4.31	34.05	-11.32	34.05
HOKI	170.98	-42.71	-3.65	43.58	-4.02	44.57
HOLD	175.52	-40.90	-24.31	30.19	-23.73	30.19
KAIK	173.53	-42.43	-29.24	31.65	-29.24	31.65
KAPT	174.91	-40.86	-12.30	38.18	-17.96	36.57
KORO	175.42	-40.41	-10.00	33.29	-15.33	33.29
LKTA	172.27	-42.78	-22.48	32.92	-22.78	32.92
LEVN	175.24	-40.59	-9.82	33.65	-18.10	33.65
MAHA	173.79	-41.29	-3.21	40.22	-13.83	38.43
MANG	175.57	-40.67	-18.18	32.70	-23.03	32.70
MAST	175.58	-41.06	-27.19	29.57	-27.19	29.57
MNHR	176.22	-40.47	-19.09	27.81	-23.83	29.16
MTBL	175.54	-40.18	-6.57	36.83	-15.11	32.16
MTQN	175.24	-41.00	-18.58	32.67	-24.24	33.40
NLSN	173.43	-41.18	-4.93	40.81	-8.87	41.25
NRRD	175.76	-40.39	-11.86	32.23	-22.01	32.41
NRSW	176.20	-40.11	-8.61	31.54	-17.12	33.40
OHIN	175.79	-39.92	-3.36	34.38	-13.58	30.08
OKOH	174.06	-41.02	-6.24	45.37	-12.99	39.24
OROA	176.68	-40.10	-12.96	26.43	-16.94	27.67
OTAK	175.17	-40.82	-14.78	35.88	-21.94	34.27
PAEK	174.95	-41.02	-17.45	35.66	-21.61	34.86
PALI	175.25	-41.57	-34.82	30.70	-34.20	30.70
PARW	175.43	-41.38	-33.62	30.73	-33.62	30.73
PAWA	176.86	-40.03	-7.04	23.29	-23.03	25.29
PKNO	175.18	-39.80	-2.15	38.69	-8.69	37.45

Table 11.3 continued from previous page

Station	Longitude	Latitude	SSE:	SSE:	Inter SSE:	Inter SSE:
			E(mm/yr)	N(mm/yr)	E(mm/yr)	N(mm/yr)
PNUI	176.20	-39.92	-6.21	29.93	-15.00	28.91
PORA	176.64	-40.27	-16.46	24.71	-19.89	26.75
PTOI	176.00	-40.60	-23.21	29.02	-24.86	29.02
RDLV	175.40	-41.19	-29.97	29.71	-29.97	29.71
TAKP	175.96	-40.06	-8.61	31.24	-15.99	31.97
TEMA	175.89	-41.11	-28.73	28.29	-28.73	28.29
TINT	175.89	-40.78	-24.60	29.38	-25.95	30.15
TKHL	172.96	-41.03	-4.78	42.12	-4.78	42.12
TORY	174.28	-41.19	-11.39	39.31	-15.80	39.31
TRAV	175.69	-41.40	-34.02	30.04	-34.02	30.04
TRWH	174.63	-41.28	-23.47	35.99	-23.14	37.23
TURI	176.38	-40.26	-14.49	27.96	-19.82	28.58
WANG	174.82	-39.79	-1.97	38.73	-6.24	40.73
WEST	171.81	-41.74	-2.37	42.30	-2.59	42.30
WGTM	174.81	-41.32	-23.98	33.73	-24.75	33.69
WHVR	175.45	-39.73	-1.50	39.24	-7.70	44.60
WITH	173.98	-41.56	-17.52	37.12	-17.52	37.60
WPAW	176.54	-39.90	-9.45	27.67	-20.26	28.36
WPUK	176.44	-40.06	-11.50	28.00	-18.14	31.28

Table 11.4: cGPS station velocities including and excluding SSEs in an Australian plate Reference Frame

Station	Longitude	Latitude	SSE	SSE	Inter SSE	Inter SSE
			E(mm/yr)	N(mm/yr)	E(mm/yr)	N(mm/yr)
AKTO	176.46	-40.54	-26.71	-12.07	-24.81	-12.07
AVLN	174.93	-41.20	-21.45	-6.78	-24.81	-6.42
BIRF	176.25	-40.68	-25.64	-10.16	-27.98	-10.16
BTHL	175.14	-41.34	-30.67	-9.37	-30.67	-9.37
CAST	176.20	-40.91	-27.51	-10.05	-28.57	-10.30
CLIM	175.15	-41.14	-23.63	-8.41	-25.97	-8.41
CMBL	174.21	-41.75	-23.91	-8.46	-23.91	-8.46
DNVK	176.17	-40.30	-15.51	-10.84	-18.22	-8.03
DURV	173.92	-40.80	-5.89	-0.46	-10.31	-0.46
GLDB	172.53	-40.83	-2.51	0.41	-3.79	0.41
GNBK	175.24	-40.08	-4.62	-5.60	-11.70	-5.60
GRNG	175.46	-39.98	-5.02	-6.05	-12.03	-6.05
HOKI	170.98	-42.71	-3.83	0.18	-4.19	1.17

Table 11.4 continued from previous page

Station	Longitude	Latitude	SSE	SSE	Inter SSE	Inter SSE
			E(mm/yr)	N(mm/yr)	E(mm/yr)	N(mm/yr)
HOLD	175.52	-40.90	-24.08	-9.88	-23.49	-9.88
KAIK	173.53	-42.43	-28.42	-9.91	-28.42	-9.91
KAPT	174.91	-40.86	-12.38	-2.35	-18.04	-3.95
KORO	175.42	-40.41	-10.30	-6.85	-15.63	-6.85
LKTA	172.27	-42.78	-21.94	-9.56	-22.23	-9.56
LEVN	175.24	-40.59	-10.02	-6.62	-18.30	-6.62
MAHA	173.79	-41.29	-3.39	-1.14	-14.01	-2.93
MANG	175.57	-40.67	-18.15	-7.32	-23.00	-7.32
MAST	175.58	-41.06	-26.76	-10.45	-26.76	-10.45
MNHR	176.22	-40.47	-18.97	-11.71	-23.71	-10.36
MTBL	175.54	-40.18	-7.05	-3.22	-15.59	-7.89
MTQN	175.24	-41.00	-18.37	-7.61	-24.02	-6.88
NLSN	173.43	-41.18	-5.38	-0.82	-9.32	-0.38
NRRD	175.76	-40.39	-12.03	-7.65	-22.18	-7.47
NRSW	176.20	-40.11	-8.86	-8.00	-17.37	-6.14
OHIN	175.79	-39.92	-3.98	-5.47	-14.20	-9.78
OKOH	174.06	-41.02	-6.56	4.21	-13.31	-1.93
OROA	176.68	-40.10	-13.00	-12.74	-16.98	-11.50
OTAK	175.17	-40.82	-14.79	-4.45	-21.94	-6.06
PAEK	174.95	-41.02	-17.35	-4.83	-21.51	-5.64
PALI	175.25	-41.57	-34.03	-9.57	-33.41	-9.57
PARW	175.43	-41.38	-32.94	-9.40	-32.94	-9.40
PAWA	176.86	-40.03	-7.08	-15.74	-23.07	-13.73
PKNO	175.18	-39.80	-3.16	-1.63	-9.70	-2.87
PNUI	176.20	-39.92	-6.65	-9.61	-15.45	-10.63
PORA	176.64	-40.27	-16.36	-14.49	-19.79	-12.45
PTOI	176.00	-40.60	-23.06	-10.68	-24.70	-10.68
RDLV	175.40	-41.19	-29.49	-10.44	-29.49	-10.44
TAKP	175.96	-40.06	-9.02	-8.48	-16.39	-7.75
TEMA	175.89	-41.11	-28.11	-11.49	-28.11	-11.49
TINT	175.89	-40.78	-24.32	-10.40	-25.67	-9.63
TKHL	172.96	-41.03	-5.61	0.14	-5.61	0.14
TORY	174.28	-41.19	-11.43	-1.69	-15.85	-1.69
TRAV	175.69	-41.40	-33.20	-9.89	-33.20	-9.89
TRWH	174.63	-41.28	-23.27	-4.75	-22.94	-3.51
TURI	176.38	-40.26	-14.50	-11.44	-19.83	-10.82
WANG	174.82	-39.79	-3.16	-1.87	-7.43	0.14

Table 11.4 continued from previous page

Station	Longitude	Latitude	SSE	SSE	Inter SSE	Inter SSE
			E(mm/yr)	N(mm/yr)	E(mm/yr)	N(mm/yr)
WEST	171.81	-41.74	-3.07	-0.51	-3.29	-0.51
WGTN	174.81	-41.32	-23.65	-6.88	-24.41	-6.92
WHVR	175.45	-39.73	-2.46	-0.88	-8.67	4.49
WITH	173.98	-41.56	-17.34	-4.10	-17.34	-3.63
WPAW	176.54	-39.90	-9.77	-11.61	-20.57	-10.91
WPUK	176.44	-40.06	-11.69	-11.36	-18.33	-8.07

Table 11.5: cGPS station co-seismic velocities in response to the KaiKoura M_w 7.8 earthquake

Station	Longitude	Latitude	Delta E	Delta N	E(mm/yr)	N(mm/yr)
AKTO	176.46	-40.54	4.470	2.310	407.89	210.79
AVLN	174.93	-41.20	1.830	51.180	166.99	4670.18
BIRF	176.25	-40.68	-5.140	2.480	-469.03	226.30
BTHL	175.14	-41.34	-16.820	39.120	-1534.83	3569.70
CAST	176.20	-40.91	-2.440	0.660	-222.65	60.23
CLIM	175.15	-41.14	-8.310	34.840	-758.29	3179.15
CMBL	174.21	-41.75	1403.710	2397.560	128088.54	218777.35
DNVK	176.17	-40.30	0.740	4.050	67.53	369.56
DURV	173.92	-40.80	16.390	57.760	1495.59	5270.60
GLDB	172.53	-40.83	33.120	-16.480	3022.20	-1503.80
GNBK	175.24	-40.08	4.390	17.500	400.59	1596.88
GRNG	175.46	-39.98	3.180	9.780	290.18	892.43
HOKI	170.98	-42.71	31.410	-5.470	2866.16	-499.14
HOLD	175.52	-40.90	-8.310	15.910	-758.29	1451.79
KAIK	173.53	-42.43	858.510	287.420	78339.04	26227.08
KAPT	174.91	-40.86	12.340	42.590	1126.03	3886.34
KORO	175.42	-40.41	2.590	15.010	236.34	1369.66
LKTA	172.27	-42.78	77.010	-0.950	7027.16	-86.69
LEVN	175.24	-40.59	6.000	21.500	547.50	1961.88
MAHA	173.79	-41.29	39.890	166.090	3639.96	15155.71
MANG	175.57	-40.67	6.450	17.400	588.56	1587.75
MNHR	176.22	-40.47	-9.980	9.230	-910.68	842.24
MTBL	175.54	-40.18	2.320	12.030	211.70	1097.74
MTQN	175.24	-41.00	-8.080	30.860	-737.30	2815.98
NLSN	173.43	-41.18	45.680	15.660	4168.30	1428.98
NRSW	176.20	-40.11	-11.020	15.190	-1005.58	1386.09
OHIN	175.79	-39.92	3.870	9.400	353.14	857.75

Table 11.5 continued from previous page

Station	Longitude	Latitude	Delta E	Delta N	E(mm/yr)	N(mm/yr)
OKOH	174.06	-41.02	17.400	121.140	1587.75	11054.03
OROA	176.68	-40.10	-3.900	2.340	-355.88	213.53
OTAK	175.17	-40.82	4.690	30.690	427.96	2800.46
PAEK	174.95	-41.02	7.340	46.790	669.78	4269.59
PALI	175.25	-41.57	-47.710	15.580	-4353.54	1421.68
PARW	175.43	-41.38	-30.130	13.360	-2749.36	1219.10
PAWA	176.86	-40.03	-2.480	5.050	-226.30	460.81
PKNO	175.18	-39.80	6.620	11.940	604.08	1089.53
PNUI	176.20	-39.92	-3.920	7.270	-357.70	663.39
PORA	176.64	-40.27	1.990	4.890	181.59	446.21
PTOI	176.00	-40.60	-0.700	6.060	-63.88	552.98
RDLV	175.40	-41.19	-28.140	21.980	-2567.78	2005.68
TAKP	175.96	-40.06	-4.370	11.500	-398.76	1049.38
TEMA	175.89	-41.11	-17.320	10.620	-1580.45	969.08
TINT	175.89	-40.78	-6.540	10.300	-596.78	939.88
TORY	174.28	-41.19	51.700	173.120	4717.63	15797.20
TRAV	175.69	-41.40	-27.980	6.670	-2553.18	608.64
TRWH	174.63	-41.28	21.040	104.760	1919.90	9559.35
TURI	176.38	-40.26	-5.440	6.510	-496.40	594.04
WANG	174.82	-39.79	5.090	16.010	464.46	1460.91
WEST	171.81	-41.74	102.920	-41.720	9391.45	-3806.95
WGTN	174.81	-41.32	0.230	70.140	20.99	6400.28
WHVR	175.45	-39.73	-0.620	9.250	-56.58	844.06
WITH	173.98	-41.56	259.910	879.100	23716.79	80217.88
WPAW	176.54	-39.90	-3.020	5.330	-275.58	486.36
WPUK	176.44	-40.06	-5.320	6.130	-485.45	559.36