Final report to the Earthquake Commission on Project 12/635

Darfield earthquake aftershocks: temporal evolution of the aftershock sequence, faulting and stress

Principal Investigator
Martha Savage, Victoria University of Wellington (VUW)

Associate investigators
John Townend (VUW), Cliff Thurber and Ellen Syracuse, (University of Wisconsin-Madison)

Contributing students
Rob Holt, MSc student
Jessica Johnson, PhD student
Rachel Heckels, PhD student
Ernestynne Walsh, MSc student

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Layman's Abstract

Data from portable deployments recording the aftershock sequence of the 4 September 2010 *Mw* 7.1 Darfield earthquake were used to determine high-resolution earthquake locations, seismic velocity models and stress in the region. Major findings were: 1) Using a three-dimensional velocity model to locate the earthquakes delineates eight individual faults active prior to the 22 February 2011 *Mw* 6.3 Christchurch earthquake, the largest aftershock of the Darfield earthquake. Two of these faults are in the Christchurch region, one of which corresponds to geodetically determined rupture planes of the Christchurch earthquake. 2) The direction of maximum compression measured by two different techniques agree with each other and show a rotation of the stress field towards nearly fault-parallel at stations close to the fault. We consider that the large drop in stress accompanying the Darfield earthquake caused a rotation of the stress near the fault after the earthquake. The changes in stress angle with distance from the fault can be used to determine that the stress dropped by 40% from its original value before the rupture. 3) The movement of seismic surface waves across the Canterbury plains is amplified by a factor of three at a period of about 2.5 s. Therefore if large structures with natural periods of vibration of 2.5 s are built in the region, we would expect that the motion from a large earthquake would similarly amplify the motion in those structures.

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Technical Abstract

The 3 September 2010 (UTC) *Mw* 7.1 Darfield (Canterbury) and 22 February 2011 *Mw* 6.2 Christchurch earthquakes and related aftershocks in Canterbury, New Zealand have revealed a major hazard in the Canterbury region in the form of the Greendale Fault and a number of associated faults. We used aftershocks of the Darfield earthquakes and ambient noise recorded on portable seismometers between 9 September 2010 and 11 January 2011 to study the earthquake occurrence patterns, seismic velocity structure, and stress in the region. We jointly inverted for three-dimensional isotropic *P*-wave and *S*-wave velocities and hypocentral locations, using data for 2840 aftershocks recorded at 36 temporary and permanent seismic stations within 70 km of the main shock epicenter. These relocations delineate eight individual faults active prior to the 22 February 2011 *Mw* 6.3 Christchurch earthquake, the largest aftershock of the Darfield earthquake. Two of these faults are in the Christchurch region, one of which corresponds to geodetically determined rupture planes of the Christchurch earthquake.

We use *P*-wave picks to estimate focal mechanisms and invert those mechanisms to estimate the azimuth of the axis of maximum horizontal compression (*SHmax*). We also use *S* waveforms to determine shear-wave splitting (SWS) parameters, whose fast orientations are also expected to be parallel to *SHmax*. Furthermore, we re-examined the paper that initially described the splitting measurement technique and published corrections to the calculation of the error bars. The tectonic stress field is remarkably uniform and has an average maximum horizontal compressive stress orientation of *SHmax* = 116 ± 18°, forming an angle with the average strike of the Greendale Fault of c. 25°. However, several *SHmax* estimates along the Greendale Fault are sub-parallel to the fault strike (93.6±13.1°, 100.8±11.5° and 100.8±12.6°), indicating that the fault may be frictionally weak, in an Andersonian sense. This variation occurs via an anti-clockwise rotation of *SHmax* southwards across the Greendale Fault. SWS fast directions (φ) generally match nearby *SHmax*, suggesting stress-aligned microcracks, but φ estimates at stations Cch3 and MQZ, which are near known and inferred faults, are subparallel to these faults and differ greatly from nearby stress orientations, indicating structure-dependent anisotropy. A lack of seismicity in the area prior to the Darfield earthquake precludes detailed analysis of time variations. However, there are two end member scenarios: if the pre-seismic stress orientation near the Greendale Fault was in the same direction as we have measured after the earthquake, then it was mis-oriented for rupture. Alternatively, if the stress rotated from the average regional orientation during the earthquake, then we can use the rotation to determine that an average of c. 40% of the pre-seismic differential stress on the Greendale Fault was released during the Darfield earthquake.

Measurement of basement seismic resonance frequencies can elucidate shallow velocity structure, an important factor in earthquake hazard estimation. Ambient noise cross correlation, which is well-suited to studying shallow earth structure, is commonly used to analyse fundamental-mode Rayleigh waves and, increasingly, Love waves. We showed via multicomponent ambient noise cross correlation that the basement resonance frequency in the Canterbury region of New Zealand can be straightforwardly determined based on the horizontal to vertical amplitude ratio (H/V ratio) of the first higher-mode Rayleigh waves. At periods of 1–3 s, the first higher-mode is evident on the radial-radial cross-correlation functions but almost absent in the vertical-vertical cross-correlation functions, implying longitudinal motion and a high H/V ratio. A one-dimensional regional velocity model incorporating a ~ 1.5 km-thick sedimentary layer fits both the observed H/V ratio and Rayleigh wave group velocity. Similar analysis may enable resonance characteristics of other sedimentary basins to be determined.

Relation to other projects

This project follows a data collection project funded by the Earthquake Commission (10/CE618) and the National Science Foundation. The initial funding was for data collection and preliminary analysis. This project has funded new analysis as well as completion of an article that was published by the New Zealand Journal of Geology and Geophysics (NZJGG) for a special edition on the Canterbury earthquake sequence.

MSc student Rob Holt was funded by the Evison Scholarship. PhD students Jessica Johnson and Rachel Heckels were funded by a Victoria University of Wellington Postdoctoral Scholarship, and MSc student Ernestynne Walsh was funded partially by a VUW MSc scholarship, partially by the Marsden Fund and partially by this grant.

Fulfilment of Objectives:

As stated in the proposal: "There are three main objectives to our proposal: 1) Determination of isotropic and anisotropic velocity structure. 2) Determination of earthquake locations and focal mechanisms. 3) Determination of the stress field through inversions of focal mechanisms and shear wave splitting orientations."

We have completed these objectives and more. We have published five papers and one MSc thesis using the Darfield aftershock dataset. The MSc thesis, by Rob Holt, received an A+. Below we list all papers published. Isotropic and anisotropic velocity structure were determined in Syracuse et al., 2013; Holt et al. 2013 and Savage et al. 2013. Earthquake locations and focal mechanisms were determined and discussed in Syracuse et al., 2012 NZJGG, Syracuse et al. 2013 JGR, and Holt et al. 2013. Shear wave splitting orientations were determined in Syracuse et al. 2012 and were more carefully investigated, along with inversions of focal mechanisms, in Holt et al. 2013. Finally, Ernestynne Walsh wrote a paper on improving the method used to determine anisotropy in the region (Walsh et al., 2013).

We have also worked a bit with Canterbury University physics PhD student John Holdaway, to examine the ring laser data at Canterbury for the time between the Darfield earthquake and the Christchurch earthquake, when the room containing the ring laser became too dangerous to work in. He presented the results at the AGU meeting and at a workshop on rotational seismology held in Christchurch in 2013.

We have worked with Marta Pischiutta to compare the anisotropy measured with shear wave splitting to differential azimuthal amplification of waves for stations near the fault plane. She presented a poster on this at AGU in 2012 and at a conference in Erice, Italy, in 2013.

PhD student Rachel Heckels has also started working with the cross-correlation data to try to determine the S-wave structure in the region and to see if there are time variations in the velocity structure, as expected if the cracks that opened during the earthquakes become sealed in the months following the event.

Abstracts of papers:

1. Crustal stress and fault strength in the Canterbury Plains, New Zealand

By R.A. Holt, M.K. Savage, J. Townend, E.M. Syracuse, and C.H. Thurber

Published in **Earth and Planetary Science Letters**

The Mw = 7.1 Darfield (Canterbury) and Mw = 6.2 Christchurch earthquakes and related aftershocks in Canterbury, New Zealand have revealed a major hazard in the Canterbury region in the form of the Greendale Fault and a number of associated faults. The strength of these apparently low slip-rate faults may affect the recurrence intervals of subsequent earthquakes. We use *P*- and *S*-wave picks from a dataset of aftershocks of the Darfield earthquake to estimate earthquake locations and focal mechanisms. We use *S* waveforms to determine shear-wave splitting (SWS) parameters and we estimate the azimuth of the axis of maximum horizontal compression (*SHmax*) from inversions of focal mechanisms. Two 2D methods of clustering the focal mechanisms for stress inversion are used, one to estimate the regional stress field and another to investigate variations in *SHmax* with distance from the Greendale Fault. A 3D method is also used to investigate variations in *SHmax* with depth. The tectonic stress field is remarkably uniform and has an average maximum horizontal compressive stress orientation of *SHmax* = 116 ± 18°, forming an angle with the average strike of the Greendale Fault of c. 25°. However, several *SHmax* estimates along the Greendale Fault from the regional 2D clustering method are sub-parallel to the fault strike (93.6±13.1°, 100.8±11.5° and 100.8±12.6°), indicating that the fault may be frictionally weak, in an Andersonian sense. This variation occurs via an anti-clockwise rotation of *SHmax* southwards across the Greendale Fault. SWS fast directions (φ) generally match nearby *SHmax*, suggesting stress-aligned microcracks, but φ estimates at stations Cch3 and MQZ, which are near known and inferred faults, are subparallel to these faults and differ greatly from nearby stress orientations, indicating structure-dependent anisotropy. A lack of seismicity in the area prior to the Darfield earthquake precludes detailed analysis of time variations. However, there are two end member scenarios: if the pre-seismic stress orientation near the Greendale Fault was in the same direction as we have measured after the earthquake, then it was mis-oriented for rupture. Alternatively, if the stress rotated from the average regional orientation during the earthquake, then we can use the rotation to determine that an average of c. 40% of the pre-seismic differential stress on the Greendale Fault was released during the Darfield earthquake.

2. High-resolution relocation of aftershocks of the Mw 7.1 Darfield, New Zealand, earthquake and implications for fault activity

By E.M. Syracuse, C.H. Thurber, C J. Rawles, M.K. Savage, and S. Bannister

Published in **Journal of Geophysical Research**

Low-slip-rate regions often represent under-recognized hazards, and understanding the progression of seismicity when faults in such areas rupture will help us to better understand earthquake rupture patterns. The 3 September 2010 (UTC) M_w 7.1 Darfield earthquake revealed a formerly unrecognized set of faults in the Canterbury region of New Zealand, an area that had previously been mapped as one of the lower-hazard areas in the country. In this study, we analyze the first four months of its aftershock sequence to identify active faults and temporal changes in seismicity along them. We jointly invert for three-dimensional P wave and S wave velocities and hypocentral locations, using data for 2840 aftershocks recorded at 36 temporary and permanent seismic stations within 70 km of the main shock epicenter. These relocations delineate eight individual faults active prior to the 22 February 2011 M_w 6.3 Christchurch earthquake, the largest aftershock of the Darfield earthquake. Two of these faults are in the Christchurch region, one of which corresponds to geodetically determined rupture planes of the Christchurch earthquake. Using focal mechanisms calculated from first-motion polarities, we find mainly strike-slip faulting events, with some reverse and normal faulting events as well. We compare the orientations of these faults to the prevailing regional stress directions to identify which faults may have been active prior to the Darfield earthquake and which may be newly developed.

3. Ambient noise cross-correlation observations of fundamental and higher-mode Rayleigh wave propagation governed by basement resonance

By Martha K. Savage, Fan-Chi Lin, and John Townend

Published in **Geophysical Research Letters**
Measurement of basement seismic resonance frequencies can elucidate shallow velocity structure, an important factor in earthquake hazard estimation. Ambient noise cross correlation, which is well-suited to studying shallow earth structure, is commonly used to analyse fundamental-mode Rayleigh waves and, increasingly, Love waves. Here we show via multicomponent ambient noise cross correlation that the basement resonance frequency in the Canterbury region of New Zealand can be straightforwardly determined based on the horizontal to vertical amplitude ratio (H/V ratio) of the first higher-mode Rayleigh waves. At periods of 1–3 s, the first higher-mode is evident on the radial-radial cross-correlation functions but almost absent in the vertical-vertical cross-correlation functions, implying longitudinal motion and a high H/V ratio. A one-dimensional regional velocity model incorporating a ~ 1.5 km-thick sedimentary layer fits both the observed H/V ratio and Rayleigh wave group velocity. Similar analysis may enable resonance characteristics of other sedimentary basins to be determined.

4. Temporal and spatial evolution of hypocentres and anisotropy from the Darfield aftershock sequence: Implications for fault geometry and age

By E.M. Syracuse, R.A. Holt, M.K. Savage, J.H. Johnson, C.H. Thurber, K. Unglert, K.N. Allan, S. Karaliyadda, and M. Henderson

Published in the **New Zealand Journal of Geology and Geophysics**

The first four months of aftershocks of the Darfield earthquake have been studied using data from temporary and permanent seismic stations to investigate the fault geometry, stress field and evolution of seismicity and seismic properties. Earthquake relocations illuminate fault segments and show that the majority of aftershocks occurred beyond the areas of highest slip during the Darfield earthquake. Seismic anisotropy shows a mixture of fast directions parallel to the maximum horizontal stress and fault-parallel fast directions. This, combined with the lack of observable growth of seismicity along fault segments, suggests that the Greendale Fault broke a pre-existing fault plane.

5. Silver and Chan revisited

By E. Walsh, R. Arnold, and M. K. Savage

Published in the **Journal of Geophysical Research**

Seismic shear waves emitted by earthquakes can be modeled as plane (transverse) waves. When entering an anisotropic medium, they can be split into two orthogonal components moving at different speeds. This splitting occurs along an axis, the fast polarization, that is determined by geologic conditions. We present here a comprehensive analysis of the Silver and Chan (1991) method, used to obtain shear wave splitting parameters, comprising theoretical derivations and statistical tests of the assumptions used to construct the standard errors. We find discrepancies in the derivations of equations in their article, with the most important being a mistake in how the standard errors are calculated. Our simulations suggest that the degrees of freedom are being overestimated by this method, and consequently, the standard errors are too small. Using a set of *S* waveforms from very similar shallow earthquakes on Reunion Island, we perform a statistical analysis on the noise of these replicates and find that the assumption substantially from the noise obtained from the shear wave splitting analysis. However, we find that the estimated standard errors for the fast polarization are comparable to the spread in the fast polarization parameters between events. Delay time errors appear to be comparable to delay time estimates once cycle skipping is accounted for. Future work using synthetic seismograms with simulated noise should be conducted to confirm this is the case for earthquakes in general.

Publications and presentations acknowledging this project:

Refereed Journal Articles

Walsh, E., R. Arnold, M.K. Savage, Silver and Chan Revisited, 118, 1-16, doi: 10.1002/jgrb.50386, online Oct. 2013

Holt, R.A., M.K. Savage, J. Townend, E.M. Syracuse, C.H. Thurber, Crustal stress and fault strength in the Canterbury Plains, New Zealand, Earth and Planetary Science Letters, 383, 173-181, 2013.

Syracuse, E.M., C.H. Thurber, C.J. Rawles, M.K. Savage, S. Bannister, High-resolution relocation of aftershocks of the Mw 7.1 Darfield, New Zealand, earthquake and implications for fault activity, Journal of Geophysical Research, 118, 4184-4195, doi: 10.1002/jgrb.50301, 2013.

Savage, M.K., F.-C. Lin, J. Townend, Ambient noise cross-correlation observations of fundamental and higher-mode Rayleigh wave propagation governed by basement resonance, Geophysical Research Letters, 40(14), 3556-3561, doi: 10.1002/grl.50678, 2013.

Syracuse, E.M., R.A. Holt, M.K. Savage, J.H. Johnson, C.H. Thurber, K. Unglert, K.N. Allan, S. Karaliyadda, M. Henderson, Temporal and spatial evolution of hypocentres and anisotropy from the Darfield aftershock sequence: implications for fault geometry and age, New Zealand Journal of Geology and Geophysics, 55(3), 287-293, doi: 10.1080/00288306.2012.690766, 2012.

Thesis

Holt, Robert. Seismic anisotropy and stress of the Canterbury plains, 122 pp. submitted February 2013, MSc thesis, Victoria University of Wellington.

Conference Abstracts

Holt RA, Savage MK, Townend J, Syracuse EM, Thurber CH, Crustal stress and fault strength in the Canterbury Plains, New Zealand, poster, Eos Trans. AGU, 94(52), Fall Meet. Suppl., Abstract T53D-2614, 2013.

M. Savage, R. Holt, E. Syracuse, J. Townend, F.-C. Lin, C. Thurber, Seismicity, velocity structure and stress from broadband seismic recordings after the 4 Sept. 2012 M 71. Darfield earthquake, In Reid, CM and Wandres, A. (eds). Abstracts, Geosciences 2013 Conference, Christchurch, New Zealand. Geoscience Society of New Zealand Miscellaneous Publication 136A., p. 84, 2013.

R. Heckels, M. Savage, J. Townend, C. Juretzek, Y. Behr, Ambient noise tomography of the Darfield 2010-2011 Earthquake sequence, In Reid, CM and Wandres, A. (eds). Abstracts, Geosciences 2013 Conference, Christchurch, New Zealand. Geoscience Society of New Zealand Miscellaneous Publication 136A., p. 41, 2013.

J. Holdaway, H. Igel. M.K. Savage. J. Townend. J. Wells. R. Hurst. E.M. Syracuse. C.H. Thurber. R. Graham, Ring Laser Observations Near Christchurch, New Zealand, of Rotational Ground Motions Induced by Teleseismic and Regional Earthquakes, poster given at *Eos Trans. AGU, 93(52)*, Fall Meet. Suppl., Abstract S21B-2470, 2012.

R.A. Holt, E.M. Syracuse, M.K. Savage, J. Townend, C.H. Thurber, J.H. Johnson (2012). Indicators of Stress and Structural Anisotropy on the Canterbury Plains In: Pittari, A., Hansen, R.J. (eds). Abstracts, Geosciences 2012 Conference, Hamilton, New Zealand. Geoscience Society of New Zealand Miscellaneous Publication 134A. p. 44.

F. Lin. M.K. Savage. J. Townend. V.C. Tsai, Extracting Rayleigh wave ellipticity from ambient noise cross-correlation (Invited), Extracting Rayleigh wave ellipticity from ambient noise, talk

given at Eos Trans. AGU, 93(52), Fall Meet. Suppl., Abstract S51G-07, 2012
M. Pischiutta, M.K. Savage, A. Rovelli, R.A. Holt, E.M. Syracuse, C.H. Thurber, Wavefield polarization in seismograms of Darfield aftershocks: orthogonality relation with shear wave velocity anisotropy, poster given at *Eos Trans. AGU, 93(52)*, Fall Meet. Suppl., Abstract S21B-2461, 2012.
M. Pischiutta, M. Savage, A. Rovelli, F. Salvini, Wavefield polarization and seismic anisotropy in fault zones, 40th Workshop of the International School of Geophysics, PROPERTIES AND PROCESSES OF CRUSTAL FAULT ZONES, EMFCSC, Erice – Sicily (Italy), 18 – 24 May, 2013.
E.M. Syracuse, C.H. Thurber, M.K. Savage, Seismic tomography of the Canterbury Plains and the geometry and evolution of seismicity of the Greendale fault system, New Zealand, poster given at *Eos Trans. AGU, 93(52)*, Fall Meet. Suppl., Abstract S21B-2505, 2012.