Source studies of the ongoing (2010-2011) sequence of recent large earthquakes in Canterbury

C. Holden & J. Beavan
GNS Science New Zealand)

SUMMARY:
On September 4, 2010, a surface rupturing crustal earthquake (Mw7.1) struck the Canterbury Plain region in New Zealand's South Island (Gledhill et al. 2011). The Canterbury Plains is a region of relatively low seismicity, and the structure that ruptured was a previously unmapped fault. The earthquake has since been followed by more than 10,000 catalogued aftershocks, of which two were of magnitude 6.3. On Tuesday 22 February 2011 a destructive Mw 6.3 aftershock with shallow depth struck approximately 10 km SE of downtown Christchurch, causing extensive damage and 180 fatalities in the central city and eastern suburbs of the city. This earthquake was very energetic, with recorded maximum vertical accelerations of 2.2 g near the epicentre. It caused much larger levels of building damage, landslides, rock falls and liquefaction than the initial Mw 7.1 Darfield mainshock. On June 13 2011 a further aftershock of magnitude (ML) 6.3 struck Christchurch. It was located only a few km south-east of the previous event, and again caused extensive damage, landslides, rock falls and liquefaction. Maximum accelerations of over 2g were also recorded. On 23 December 2011 Christchurch was again struck by two large aftershocks, 2 hours apart, of magnitude (Ml) 5.8 and 6.0. These were located offshore, about 10 km east of the central city. Unlike the Mw 7.1 event no surface rupture has been found for either of the two M6.3 aftershocks. The source process of all of these events have been well constrained by geodetic and seismological data. We present an overview of the source models as well as a preliminary sequence based on the kinematic sources of the earthquakes.

Keywords: earthquake sources kinematic Canterbury strong-motion

1. INTRODUCTION

The Canterbury region has been struck by more than 10,000 M2+ earthquakes since the sequence started with the 4 September 2010 Mw 7.1 Darfield earthquake (Gledhill et al. 2010). The sequence includes the 22 February 2011 Christchurch earthquake (Mw 6.2) (Gledhill et al. 2011; Kaiser et al. 2012), the June 2011 Mw 6.0 earthquake and the December 2011 magnitude (Ml) 5.8 and 6.0 earthquakes. These events caused widespread liquefaction, landslides and heavy building damage and collapse. The Christchurch earthquake was particularly sombre with thousands of injured people and 185 people losing their life in the quake and its immediate aftermath.

The earthquakes have been well recorded by a regional dense network of strong motion and broadband instruments. Regular and dense measurements of GPS data points as well as InSAR images have constrained the ground displacements following each large event. The Canterbury earthquake ruptures have been extensively studied using strong motion data (Holden et al. 2011; Holden 2011), GPS and InSAR data (Beavan et al. 2010; Beavan et al. 2011; Beavan et al. 2012; Barnhart et al. 2011), InSAR data (Atzori et al. 2012) and InSAR and teleseismic data (Elliott et al. 2012). We present here a sequence of kinematic models of the Darfield earthquake (Holden et al. 2011), the Christchurch earthquake (Holden 2011) and new source models for the June and December 2011 events.

2. KINEMATIC SOURCE MODEL OF THE MW 7.1 DARFIELD EARTHQUAKE

The final fault model from Holden et al. (2011) (Figure 1 and Figure 7) is composed of 3 fault planes (4 segments): the Greendale fault plane, an almost vertical 30 km-long east-west striking segment (strike 266 degrees) and of a NW striking 10 km long segment to the east (strike 320 degrees), a segment striking 40 degrees (75 degree dip) and close to the epicentre (the Charing Cross segment), and a western segment near Hororata striking 220 degrees (65 degree dip). The rupture started on the steeply dipping Charing Cross blind reverse fault, and ruptured between 3 and 6 seconds. This initial sub-event was equivalent to a magnitude Mw 6.2 earthquake. Rupture then occurred along the Greendale Fault plane in a bilateral mode for about 10 seconds, between 8 and 18 seconds, reaching a maximum displacement of 5 m at the surface. The rupture directivity was strongly towards Christchurch. The slip rake is mostly right lateral with a slight normal component. This is equivalent to a magnitude Mw 6.8 event, making it the largest of the three events. After 17 seconds, the reverse fault near Hororata ruptured, reaching a maximum slip of 2.8 m at shallow depth (~1 km). This third rupture was equivalent to a Mw 5.7 event. The overall moment release for this model is equivalent to a Mw 6.9 earthquake.

The proposed segments for the Greendale, Charing Cross and Hororata faults are very similar to the static models proposed by Beavan et al. (2010, 2012), Elliott et al. (2012) and Atzori et al. (2012) suggesting an almost vertical east-west trending Greendale fault with a northwest striking western segment, as well a north-east-dipping Hororata segment and a south-west dipping Charing cross segment. However these studies suggest a fault rupture with an even more complex segmentation, which highlights the complexity of the Darfield earthquake and the need for a more detailed kinematic model to better understand the triggering mechanisms of the Darfield sequence.

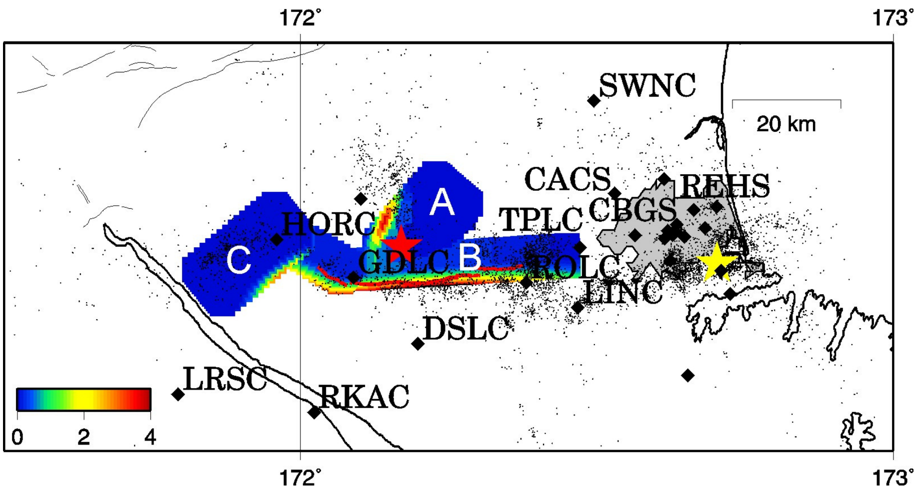


Figure 1. Map showing the surface projection of the slip distribution from the 3D seismological fault rupture model of Holden et al. (2011), the strong motion stations (black diamonds), the mapped surface trace (red), the Darfield epicentre (red star) and the Christchurch epicentre (yellow star). The black dots are relocated aftershocks from Bannister et al. (2011) up until 29 May 2011. The light grey region represents the area of Christchurch city. A is the Charing-Cross reverse fault near the epicentre, where the rupture initiated; B is the Greendale Fault plane where the rupture initiated at depth and ruptured towards Christchurch between 8 and 18 seconds; C is the fault plane near Hororata where the rupture occurred after 17 seconds and near the surface.

3. THE CHRISTCHURCH EARTHQUAKE

The Mw 6.2 earthquake occurred at 12.51 pm local time, about 8 km southeast of Christchurch city centre. The timing of the earthquake and its location near the city centre have contributed to heavy building damage, landslide, intense liquefaction and the tragic loss of lives. Holden (2011) used near-source strong motion data from 11 stations located between 2 and 20 km from the epicentre, filtered up to 1 Hz, to invert for a kinematic source model of the earthquake. The fault plane geometry was fixed following results from Beavan et al. (2011). The proposed source model consisted of one elliptical patch of slip, with maximum slip of 4.2 m at 4 km depth (Figure 2 and Figure 7). The rupture propagated up the fault plane and towards the city centre with a 135 degree slip direction. Very large and shallow slip, high rupture velocity and the rupture directivity would have contributed to the intense ground shaking in Christchurch.

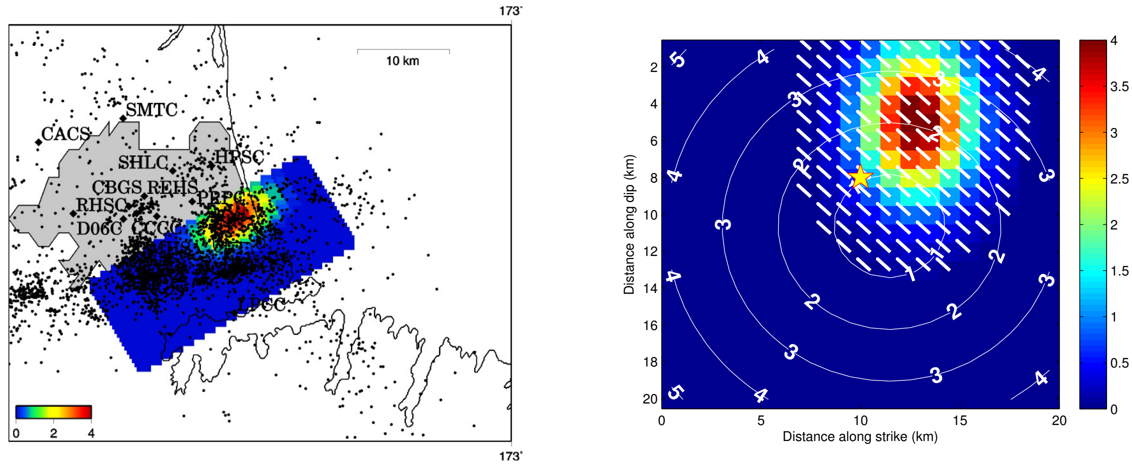


Figure 2. Left: final slip distribution on a plane oriented 59° strike and 67° dip (Holden 2011). The black dots are relocated aftershocks from Bannister et al. (2011) up until 29 May 2011. The light grey region represents the area of Christchurch city; Right: slip and rake history. Slip is shown in color, and the rake is represented by white vectors for each grid cell. Distances are in kilometers and rupture time iso-contours are in seconds. The yellow star is the relocated hypocenter from Bannister et al. (2011)

Studies by Beavan et al. (2012), Barnhart et al. (2011), Elliott et al. (2012) and Atzori et al. (2012) suggest implication of a similarly striking fault plane. However in the fault models from Elliott et al. (2012) and Atzori et al. (2012), a secondary segment with a shallower dip angle and a strike of 27° and 30° respectively also contributes to the overall earthquake sequence. Beavan et al. (2012) suggest a 3-fault model composed of 2 segments of strike 65° and dip 70° and one segment of strike 15° and dip 70°. These proposed fault configurations will be tested against strong motion data. These models are crucial to better define the extreme ground motion experienced in Christchurch, particularly for engineering applications.

3. THE JUNE AND DECEMBER EARTHQUAKES

3.1. Data and methodology

The inversion methodology is detailed in Holden (2011). We used strong motion data from 7 and 13 stations respectively for the June and the December events. The data are filtered from 0.1 to 0.5 Hz and integrated into velocities. The fault planes were constrained by the location of the hypocentres; we tested both conjugate fault geometries as determined by moment tensor solutions for each event. We invert the data for one elliptical patch of slip with various sizes and locations, various amplitudes and directions of slip and various rupture times. We present here results for the fault planes giving the best waveform fits.

3.2. The June 13th earthquake

The Mw 6.0 event struck on June 13th 2011 at 2.20 pm local time. It produced extreme horizontal accelerations of 2.1 g near the epicentre and up to 0.8 g in central Christchurch. It caused intense liquefaction, as well as cliff collapses and further landslides. There was little building damage as earthquake prone buildings had already been taken down by the February quake. There were also no casualties as hazardous areas had been cordoned off.

We tested both conjugate fault planes individually following the regional moment tensor solution of strike 71 and 161 degrees (J. Ristau pers. comm.). Using very near-source stations, and through a trial and error process we redefined the strike and dip of the 2 fault planes to 153 and 70 degrees. We inverted for each fault plane separately. Results from the two inversions were spontaneously matching a different time-window of the waveforms with the 71 degree striking fault plane contributing to the early part of the signal and the 153 degree striking plane to the later part.

The rupture for the June Mw 6.0 event is characterized by 2 fault planes rupturing a few seconds apart (Figure 3 and Figure 7). The first fault plane is oriented 70 degrees azimuth and 60 degree dip. The earthquake ruptured an elliptical slip patch of 6 by 5 km^2, and a maximum slip of 3 m at 4.6 km, between 1.5 and 3 seconds. The slip direction is 154 degrees. The total moment for this sub-event is 5.49*1017 Nm, equivalent to a Mw 5.8 earthquake. The second fault plane is oriented 153 degrees azimuth with 50 degree dip. The earthquake ruptured an elliptical slip patch of 11 by 7 km^2, and a maximum slip of 2.6 m at 3.5 km depth, between 3 and 5 seconds. The slip direction is -52 degrees. The total moment for this second sub-event is 8.49*1017 Nm, equivalent to a Mw 5.9 earthquake. The estimated magnitude for both events is Mw 6.0. Figure 4 shows the waveform fits for the contribution of individual fault planes as well as for the total contribution. The waveform fits are very satisfying for all three components. Only the very early waveform at the closest sites GODS and PARS could not be fitted. The rupture started probably very close to GODS and PARS stations with an event too small to be resolved for the low frequency bandwidth of this study.

This solution is very similar to the static 2-fault model from Beavan et al. (2012), with one fault to the north striking 67° (dip 79°), and a second one to the south striking 155° (dip 55°). Atzori et al. (2012) have modelled a single fault plane for that event, similar to the southern fault plane of the composite source model, striking 150° (dip 70°). Finally, using only teleseismic data, Elliott et al. (2012) have obtained a fault plane similar to the northern fault plane of the composite source model, striking 65° (dip 70°).

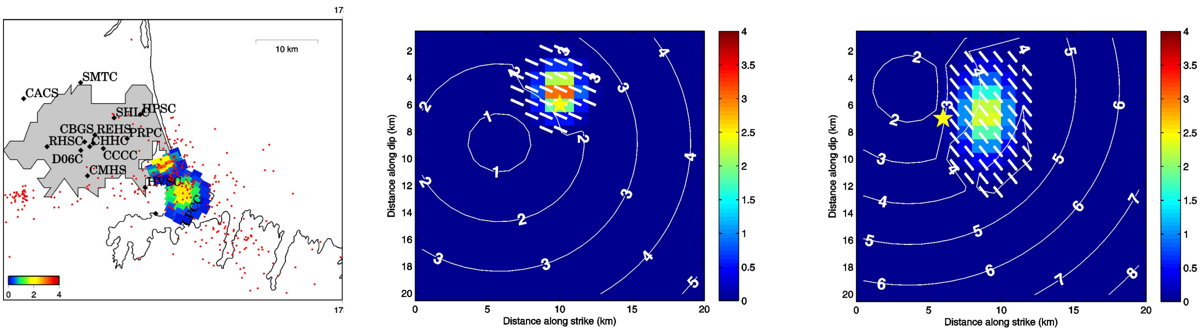


Figure 3: Left: final slip distribution for the fault planes oriented strike 70°, dip 60° (north) and strike 153° dip 50° (south). The red dots are relocated aftershocks from Bannister (pers. comm.) up until 29 May 2011. The light grey region represents the area of Christchurch city; slip and rake history for the fault planes oriented strike 70°, dip 60° (left) and strike 153° dip 50° (right). Slip is shown in color, and the rake is represented by white vectors for each grid cell. Distances are in kilometers and rupture time iso-contours are in seconds. The yellow star is the relocated hypocentre from Bannister (pers. comm.)

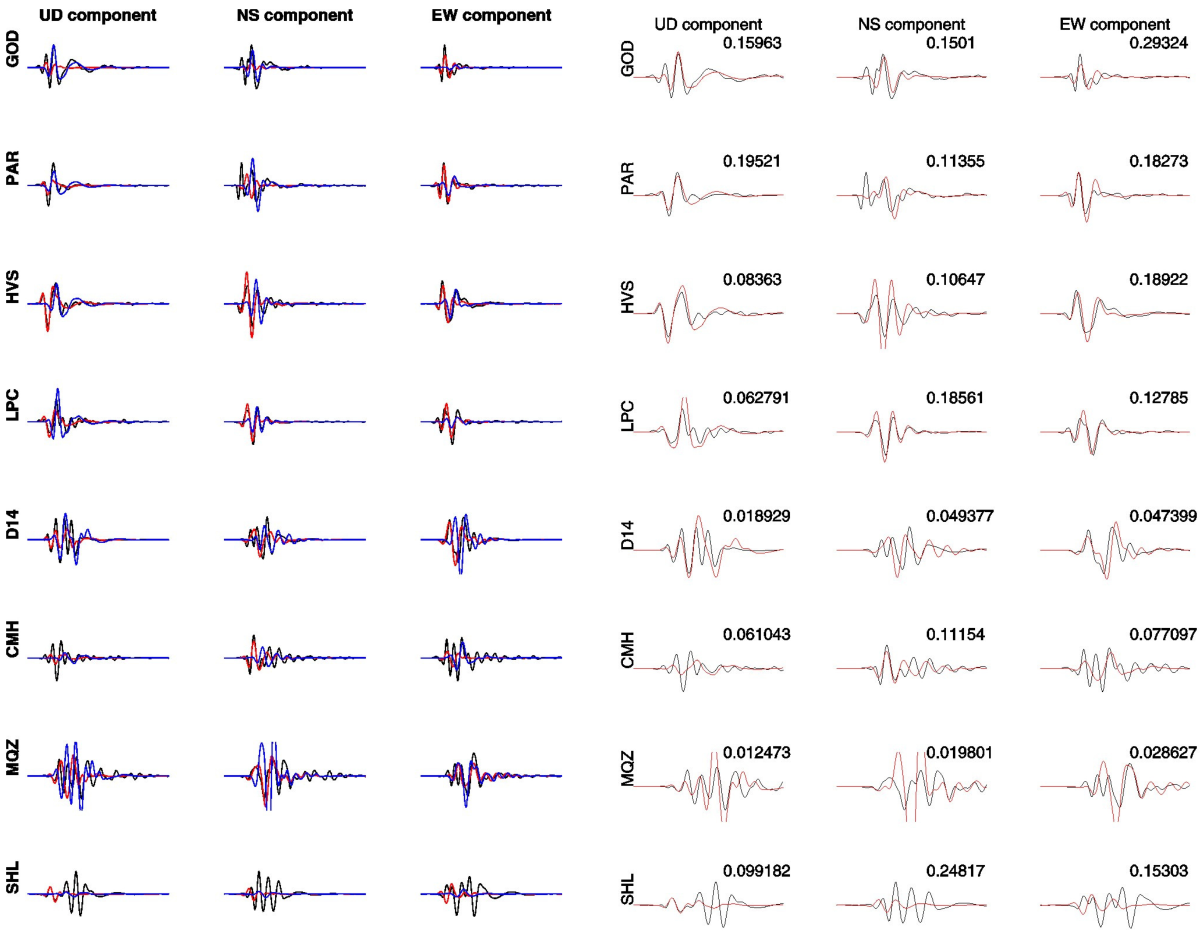


Figure 4: left: 3-component velocity seismograms (30 seconds) for the observed data (black), synthetic data from the first fault plane only (east-west) (red) and for the second fault plane only (north-south) (blue); Right: 3-component velocity seismograms (30 seconds) for the observed data (black) and synthetic data from joint fault planes (red). Values above the traces are the maximum observed absolute velocities (m/s).

3.3. The December earthquake

The M6.0 (Mw 5.9) December 2011 earthquake struck Christchurch on 23 December at 3:18 pm local time. It was centred 10 km east of downtown Christchurch and was preceded 2 hours earlier by an Mw 5.8 foreshock.

We tested both conjugate fault planes individually following the regional moment tensor solution of strike 57 and 191 degrees (J. Ristau pers. Comm.). The fault plane striking 57^o and dipping 51^o (Figure 5 and Figure 7) gave the best waveform fits (Figure 6-a). The geometry of the fault plane is also supported by the relocated aftershocks following the December 23rd event (Figure 6-b) from Ristau et al. (2012). They clearly highlight a north-east striking south-west dipping fault plane. The rupture for the December Mw 5.9 event is characterized by an elliptical slip patch of 18 by 15 km^2, and a maximum slip of 0.8 m at 3.5 km depth. The slip direction is 127 degrees. The rupture propagated up the fault plane. The total moment is 1.42*10^{18} Nm, equivalent to a Mw 6.0 earthquake. The peak accelerations were horizontal with up to 0.65 g at HVSC, a site a few kilometres south of the epicentre. Accelerations were actually larger for the Mw 5.8 earthquake that occurred about 2 hours earlier at 12:58 pm, with peak acceleration of 0.95 g. The December event is similar to the February event and the northern fault plane of the June event, being oblique reverse/right-lateral faulting, shallow, with large slip and similar strike. This model is similar to the one proposed by Beavan et al. (2012) using InSAR and GPS with a fault plane striking 70^o (dip 73^o) (but which is only well constrained at its western end).

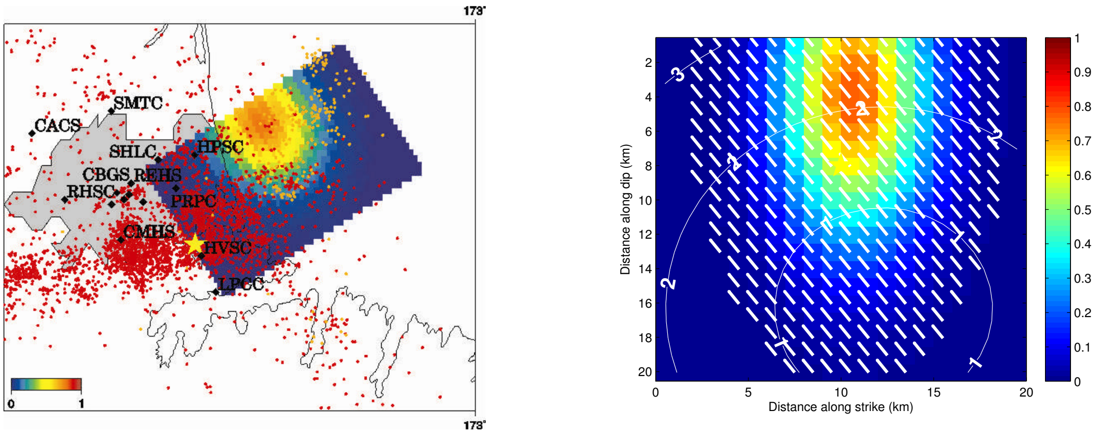
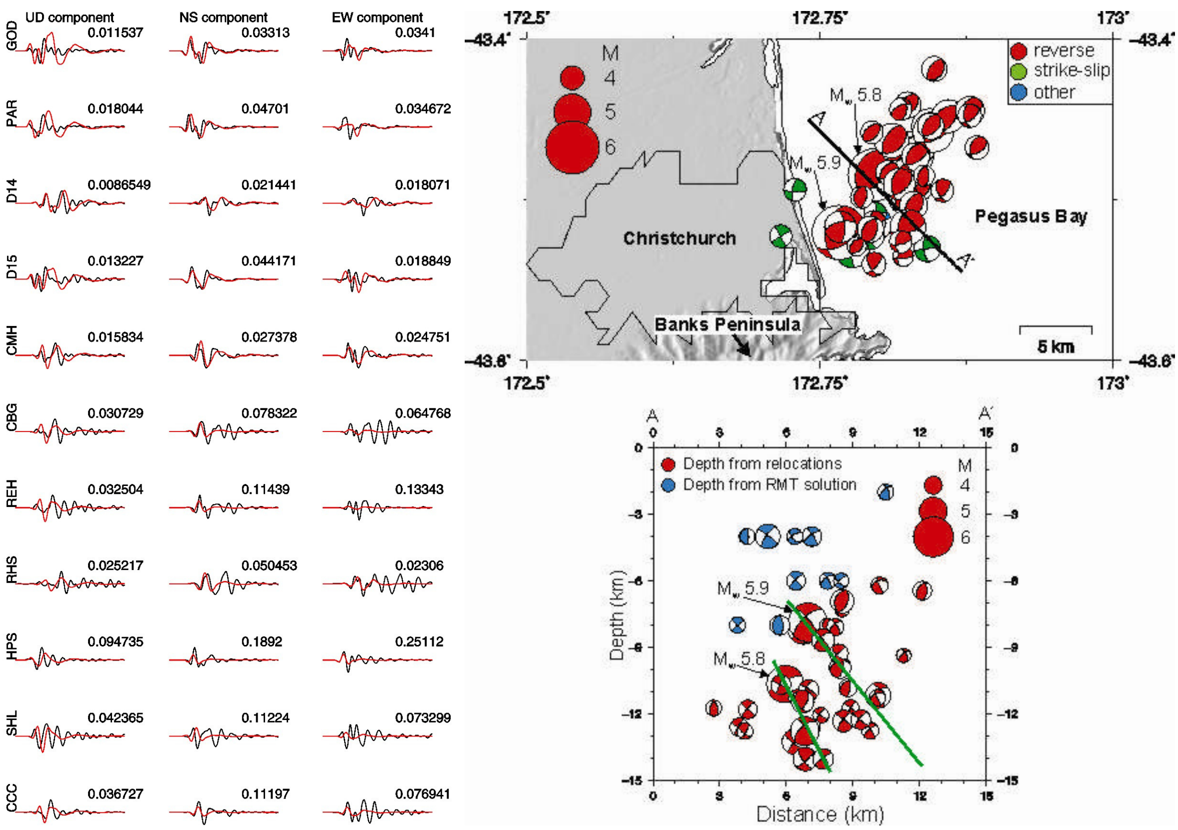


Figure 5. Final slip distribution on a plane oriented 57° strike and 51° dip. The red dots are relocated aftershocks from Bannister (pers. comm.) from Dec. 23rd up until Jan. 4th 2012. The light grey region represents the area of Christchurch city. Right: Slip and rake history. Slip is shown in color, and the rake is represented by white vectors for each grid cell. Distances are in kilometers and rupture time iso-contours are in seconds. The yellow star is the relocated hypocenter from Bannister (pers. comm.).



a) b)

Figure 6: a) 3-component velocity seismograms (30 seconds) for the observed data (black) and synthetic data for the fault plane oriented strike 57°, dip 51° (red). A resonant period of about 3 seconds is noticeable on "soft site" horizontal recordings (Cousins and McVerry 2010). Values above the traces are the maximum observed absolute velocities (m/s). **b)** relocated aftershocks following the December 23rd 2011 earthquakes and their focal mechanism solution (Ristau et al. 2012)

5. SUMMARY OF THE SEQUENCE

The Canterbury earthquake sequence began with the Mw 7.1 Darfield earthquake that ruptured the Greendale fault across the Canterbury Plains, about 30 km west of downtown Christchurch. It has been since followed by three large aftershocks, located very close to Christchurch and around Lyttelton volcano on Banks Peninsula (Figure 7). All these events were very shallow and released a great deal of energy, contributing to intense ground shaking in Christchurch (Fry et al. 2011). However the latest large aftershocks seem to lose strength in energy (Fry and Gerstenberger 2011 and B. Fry, pers. comm.). The strike, dip, rake and depth of maximum slip for the February Mw 6.2 earthquake, one fault plane of the June event and the December M6.0 aftershock are very close (59/67/154-4 km, 70/60/135-4.6 km, 57/51/127-3.5 km respectively). These events all belong to the same tectonic environment marked by a deep brittle-ductile transition (Reyners and Cowan 1993) as well as the presence of the Banks Peninsula volcano. We suggest that the intrusion of the volcano has not only highly segmented faults in the region near Christchurch, but may have also brought closer to the surface the very brittle and dehydrated Hikurangi plateau (Reyners et al. 2011). However Ristau et al. (2012) also propose that these faults might be the southern extension of the mapped reversed-faulting structures in North-Canterbury from Pettinga et al. (2001).

Another characteristic of the sequence is the epicentres clearly propagating to the east, with the latest occurring offshore of Christchurch. Figure 8 shows static Coulomb Stress changes from the Darfield fault sequence (Beavan et al. 2010), the February earthquake (Beavan et al. 2011) and a preliminary fault solution from the June earthquake (Beavan pers. comm.) onto receiver faults oriented 60 degree strike and 70 degree dip (S. Steacy, pers. comm.). The February, June and December events are all located in areas of only very small Coulomb stress increase (0.1 MPa). Using more detailed fault models, we hope to better define the influence of static stress in the Canterbury earthquake sequence. We should also note that each of the February, June and December earthquakes has been preceded or followed by many large aftershocks suggesting a combination of static and dynamic triggering. We hope to better understand this point by combining detailed static and kinematic models.

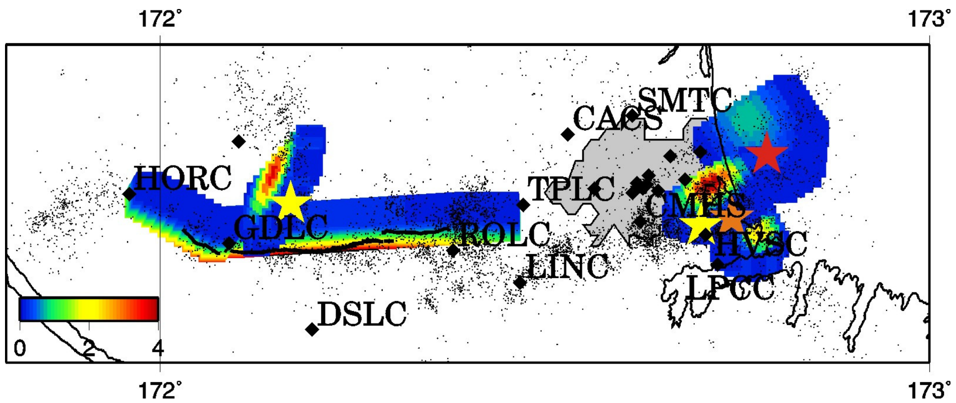


Figure 7. Final slip distribution for the 2010-2011 Canterbury earthquake sequence. The yellow star to the left is the Darfield epicentre, the yellow star to the right and the orange and red stars are epicentres for the February, June and December earthquakes respectively. Black diamonds are strong motion stations. The black dots are partly relocated aftershock up until Jan. 04th 2012 (Bannister pers. comm.).

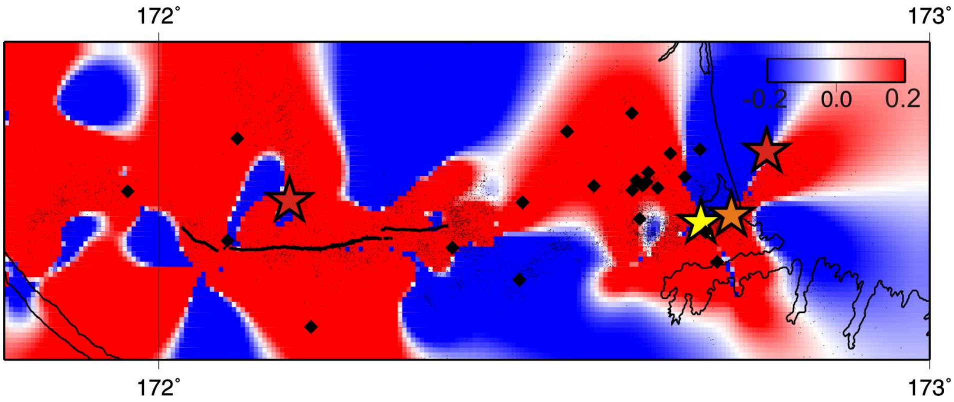


Figure 8. Static Coulomb stress changes (bars) from the Darfield fault sequence (Beavan et al. 2011), the February earthquake (Beavan et al. 2011) and a preliminary fault solution from the June earthquake (Beavan, pers. comm.) onto receiver faults oriented 60 degree strike and 70 degree dip (S. Steacy pers. comm.). The yellow star to the right and the orange and red stars are epicentres for the February, June and December earthquakes respectively. The black dots are partly relocated aftershock up until Jan. 04th 2012 (Bannister, pers. comm.).

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