GNS SCIENCE
TE PŪ AO

Relocation Analysis of the Christchurch City "Boxing Day" Earthquakes

Stephen Bannister

GNS Science Consultancy Report 2011/36
March 2011

BIBLIOGRAPHIC REFERENCE

Bannister, S.; 2011. Relocation analysis of the Christchurch City "Boxing Day" earthquakes, *GNS Science Consultancy Report* 2011/36. 10 p.

CONTENTS

FIGURES

EXECUTIVE SUMMARY

All earthquakes catalogued by GeoNet that occurred near and beneath Christchurch city between Christmas Day 2010 and 5th February 2011, were relocated using a "double-difference" location procedure, in order to examine their absolute and relative hypocentre locations. The location analysis of these events may possibly assist interpretation of fault structure beneath the city.

The sequence, termed here the "Boxing Day sequence", began with a local magnitude (M_L) 4.9 earthquake on Boxing Day 2010, with M_L4.6 and M_L4.4 events just a few hours later. More than 30 events followed in close spatial proximity over the subsequent 3-4 weeks. The relocation analysis indicates that the M_L4.9 event was located at ~4.0 km depth with an epicentre 1.8 km NW from Christchurch cathedral. Most of the subsequent events occurred at depths between 3.5 and 7 km, and occurred in a single patch less than 1 km^2 in area, with epicentres ~1 km NE of Christchurch cathedral. Projections of the events indicate a steeply dipping cluster, which is consistent with one of the nodal planes of the M_L4.9 event (strike 74°, dip 84°, rake 153°). These relocations suggest that the events represent strike-slip rupture on a steeply dipping fault with strike ~74°, with activity on that fault spread over a distance of ~2.5 km.

1.0 INTRODUCTION

The M_w7.1 Darfield earthquake occurred at 16:35 September 3rd UT, 2010, within 40 km of Christchurch city. The event was well recorded by the broadband and strong-motion national-scale GeoNet network (Petersen et al., 2011) as well as by the Canterbury regional strong-motion network (Avery et al., 2004). A surface rupture, now named the Greendale fault, was observed 4 km south of the epicentre. The rupture is consistent with strike-slip faulting with an average horizontal displacement of ~2.5 m (Quigley et al., 2010), extending for ~29.5 km. However, seismological, geodetic and InSAR information all suggest that the earthquake rupture process involved rupture of multiple fault segments (Caroline Francois Holden pers. comm., Martin Reyners pers. comm., Beavan et al., 2010, Gledhill et al., 2011). Research currently in progress at GNS Science will likely resolve the full complexity of the rupture process of the Darfield earthquake.

The Darfield earthquake has since been followed by more than 4000 located aftershocks (as of the end of January 2011) (Figure 1). There have been more than 14 aftershocks of local magnitude (M_L) 5.0 or greater and 155 aftershocks with M_L 4.0–5.0. The majority of aftershocks are shallow, at less than 15 km depth. Figure 1 shows that many of the aftershocks are near the surface trace of the Greendale fault, but that there are also intense clusters of activity west of the western end of the fault trace, and also at the eastern end of the fault trace. There is also a "finger" of aftershocks trending NNW from the mainshock epicentre.

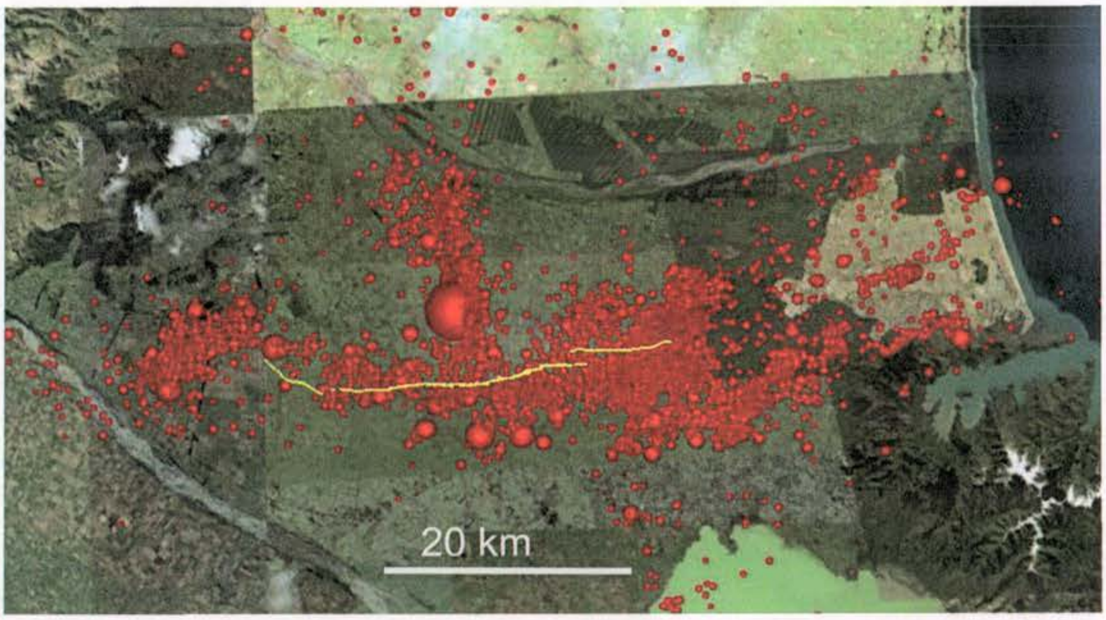

Figure 1 All catalogued earthquakes in the Christchurch region between September 4th 2010 and February 5th 2011. The earthquake symbol sizes are scaled with magnitude. The earthquake epicentres shown in this figure were refined from the standard GeoNet locations by using the differential travel times of the P and S seismic phases, together with a 1-d velocity model, using the double-difference location procedure of Waldhauser and Ellsworth (2000). The focus of this report is the earthquakes beneath Christchurch city centre – the built-up area of the city is visible as a light grey patch on the right hand side of the figure. The yellow line marks the surface rupture of the September M7.1 mainshock, which was subsequently named the Greendale fault.

On February 22^{nd} 2011, a M6.3 earthquake occurred, with a hypocentre ~ 7 km south-east of the centre of Christchurch city. There were 165 known fatalities (as of 7^{th} March), and at least 300 aftershocks, including several events with magnitudes greater than 5. This report will not examine this earthquake or the subsequent aftershocks, but will instead focus on the 2010 Boxing Day sequence.

2.0 BOXING-DAY SEQUENCE

On 26 December 2010, as part of the ongoing aftershock activity, a cluster of shallow aftershocks occurred near the Christchurch city centre. The largest of these events had a local magnitude of M_L4.9, and caused a significant amount of damage in the city centre. Figure 2 shows the locations of earthquakes catalogued by GeoNet that occurred between December 25^{th} 2010 and February 5th 2011 beneath the city. The main cluster of earthquakes lies directly beneath central Christchurch city.

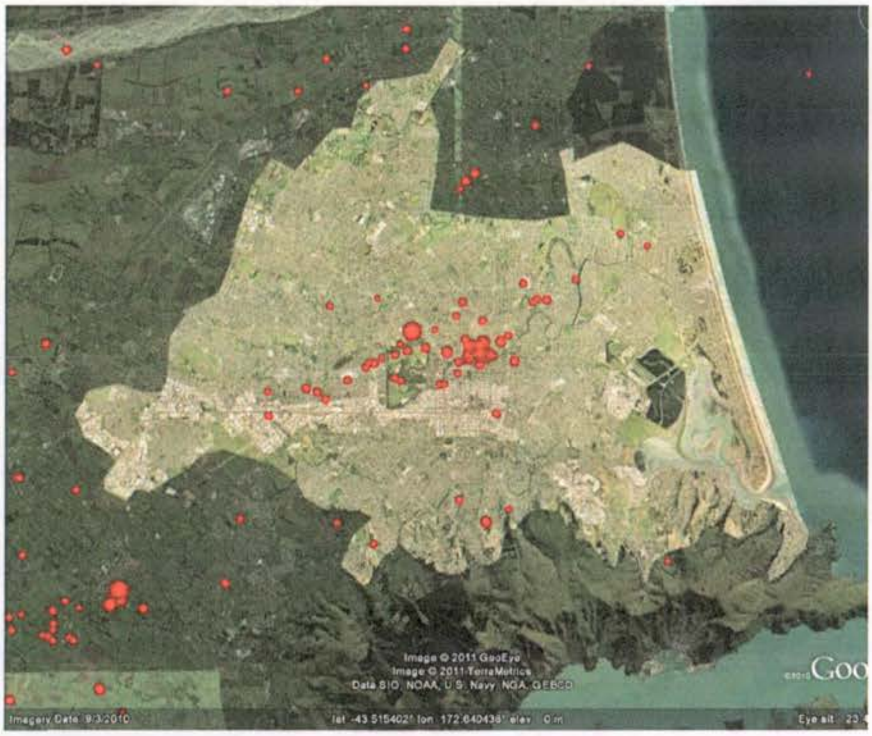

Figure 2 Locations of all earthquakes (catalogued by GeoNet) that occurred beneath Christchurch city between 25/12/2010 00:00 UTC and 5/2/2011 23:59 UTC. The main cluster of earthquakes, with more than 25 events, lies directly beneath central Christchurch city; the epicentres of this cluster are less than 1 km from Christchurch cathedral and the hypocenters are between 3.5 and 7 km deep.

The earthquake epicentres shown here are those derived from re-analysis and relocation of waveform data originally recorded by GeoNet. Arrival times of P and S seismic phases were manually examined for all events shown in this figure. The events were then relocated using the most recent version of the 3-D New Zealand velocity model (Eberhart-Phillips et al., 2010) using the double-difference tomography approach of Zhang et al. (2009).

2.1 Analysis of Boxing Day sequence

The event locations shown in Figure 2 were derived from re-analysis and relocation of data obtained from GeoNet. The picks of all events shown in this figure were re-examined manually. The events were then relocated using the most recent version of the 3-D New Zealand velocity model (Eberhart-Phillips et al., 2010) using the double-difference tomography approach of Zhang et al. (2009), which built on earlier work by Zhang and Thurber (2003). The technique in their approach minimises the residuals between observed and calculated arrival-time differences for pairs of closely located earthquakes, while also minimising the residuals of absolute arrival times. The algorithm solves for the hypocentral parameters of the earthquakes, allowing some modification of the regional P-wave and S-wave velocities used for travel-time calculation. Initial hypocentre locations for the analysis were those determined by GeoNet. Most events were only well recorded by 3 or 4 GeoNet stations if they were below the threshold for detection by the Canterbury strong-motion network – more than 49 events had less than 8 phase picks. Larger magnitude events were recorded by the Canterbury strong motion network – more than 30 events had 20 or more phase picks.

Catalogue-based differential times (CTDT) were calculated between events initially separated by less than 10 km, for all stations less than 150 km from the cluster centroid, using the manually picked P- and S- arrival times (Figure 3).

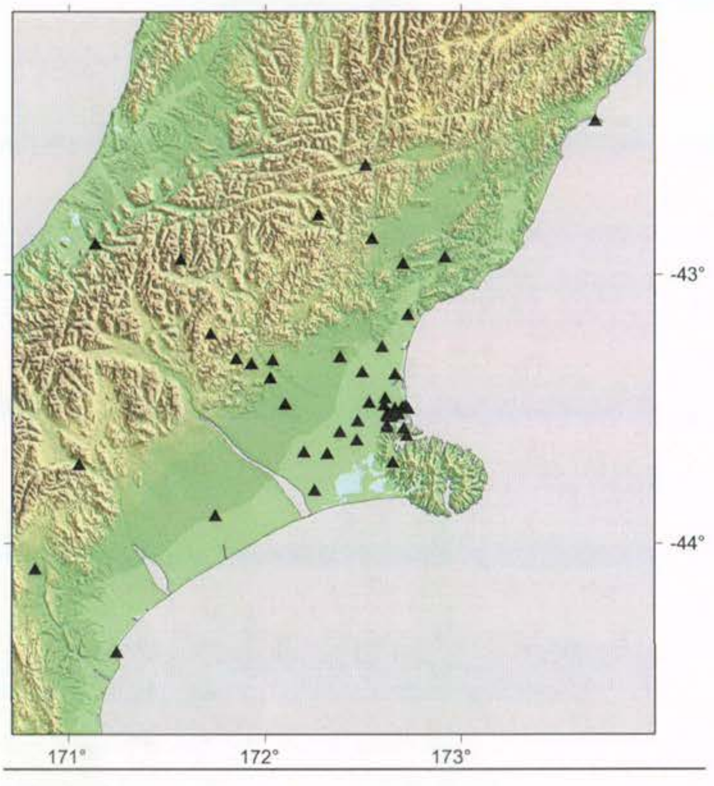

Figure 3 Seismometer stations for which data was used in the double-difference location analysis. Seismic waveforms from all Boxing Day events observed at these stations were cross-correlated, for use in the relocation. Data from stations at larger distances (e.g. >150 km) do not greatly assist in constraining the relative locations of the earthquakes.

In addition, cross-correlation and bispectrum (BS) (Du et al., 2004) methods were then used to calculate the waveform-based differential times (WBDT) for all event-station pairs, after pre-filtering, following the technique of Du et al. (2004). These derived differential times were weighted based on the quality of the arrival time measurements.

Absolute travel times and the two types of differential times (CTDT and WBDT) were then combined and simultaneously inverted using the approach of Zhang et al. (2009) in an iterative least-squares procedure which utilises the LSQR method (Paige and Saunders, 1982). The final full data set was comprised of 444 events with 114984 differential times of which 25400 were cross-correlation differential times.

The velocity structure used as the 3-D velocity model for the relocation was based on the velocity model of Eberhart-Phillips et al. (2010), which is publicly accessible in the supplement of that article. For this analysis, that New Zealand-wide velocity model was linearly interpolated to a new dense rectilinear grid centred on Christchurch city, specifically for the purposes of this relocation analysis. Interpolation of the velocity model was carried out using the python mlab routine *mlab.pipeline.delaunay3d*, which calculates delauney triangulation, so allowing the velocity volume to be probed for a velocity value at any point of interest (Python web reference, 2011). Our finer velocity model grid has a minimum grid spacing of 10 km along the x- and y-axes, in the section of the volume near the Boxing Day events, and grid layers at 0, 2, 4, 8, 12, 24, and 30 km depth, fully encompassing the Boxing Day sequence.

The relocated epicentres are shown in Figure 2. Figure 4 shows the same data set, but displaying a greater spatial area.

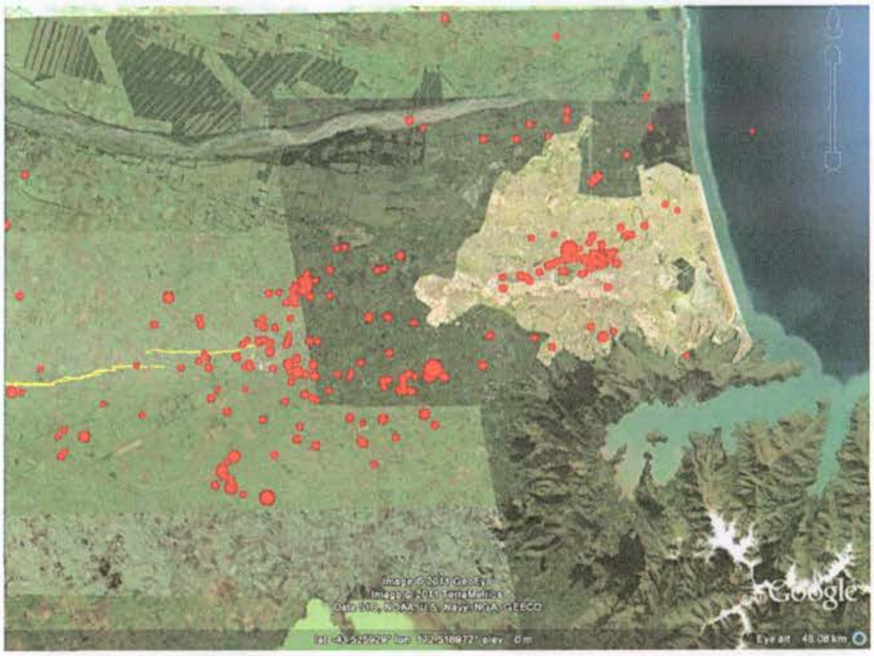

Figure 4 Event locations, as for figure 2 above, but displaying a greater spatial area. The majority of events west of the city boundaries occurred in January 2011, and were scattered in time.

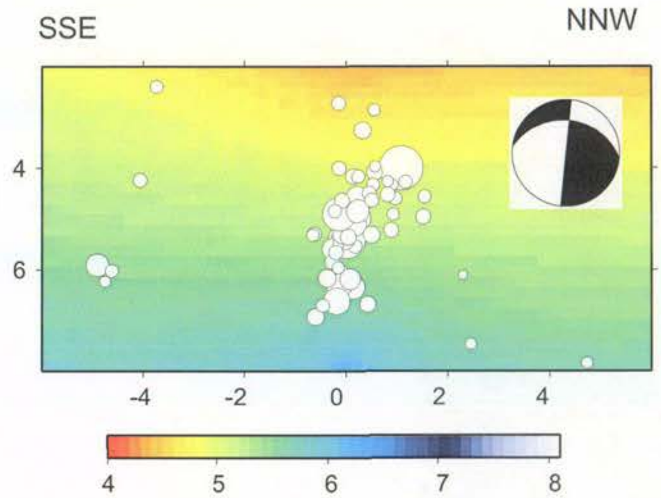

Figure 5 Earthquake hypocentres plotted onto a vertical plane with strike 344 degrees. The P-wave velocity structure used in the earthquake relocation is also shown, with P-wave speeds ranging from 4 to 6 km/s in the depth range 2 to 8 km. The 'beachball' is a representation of the M_L 4.9 Boxing Day earthquake (cuspid 3437105) as a side view, using a view angle of N76E. The dipping events have a similar dip to the nodal plane of the M_L4.9 event. The details of the moment tensor solution for this event can be found in the GeoNet moment tensor data repository (2011).

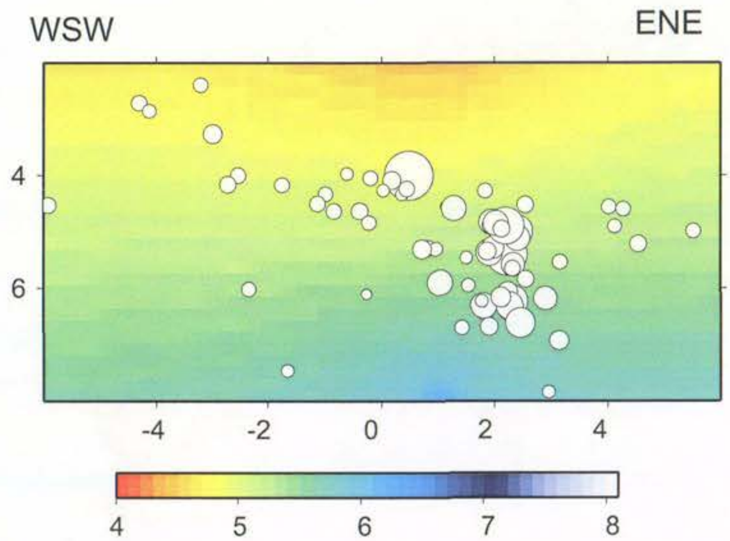

Figure 6 Earthquake hypocentres projected onto a vertical plane with strike 74 degrees. The P-wave velocity structure used in the earthquake relocation is also shown. The M_L4.9 event is ~1.5 km to the west of the main cluster of events (which include events of magnitude M_L4.6 and M_L4.4).

The relocation analysis, represented in Figures 2, 4, 5 and 6, indicates that the initial Boxing Day M_L4.9 event was located at ~4.0 km depth with an epicentre 1.8 km NW from Christchurch cathedral. Most of the subsequent events occurred over a depth range between 3.5 and 7 km, and occurred in a single patch less than 1 km^2 in area, with epicentres ~1 km NE of Christchurch cathedral. Projections of the events indicate a steeply dipping cluster, which is consistent with one of the nodal planes of the M_L4.9 event (strike 74°, dip 84°, rake 153°) previously inferred from moment tensor analysis (GeoNet repository 2011). These earthquake relocations suggest that the events represent strike-slip rupture on a steeply dipping fault with strike ~74°, with activity on that fault spread over a lateral distance of ~2.5 km. To the east of Christchurch city the visual alignment of locations of (less than 25) earthquakes suggest that the M_L4.9 fault noted above may possibly extend up to 7 km ENE of the city.

For further context, Figure 7 shows the full distribution of the Darfield aftershocks, as well as the first week of aftershocks following the February 22nd M6.3 earthquake. The Boxing Day sequence lies ca. 4 km north of the large sequence of aftershocks following the February 22nd earthquake. It is clear that the full sequence following the September mainshock is incredibly complex, and that the Boxing Day events represent only a small part of the redistribution of stress following that mainshock.

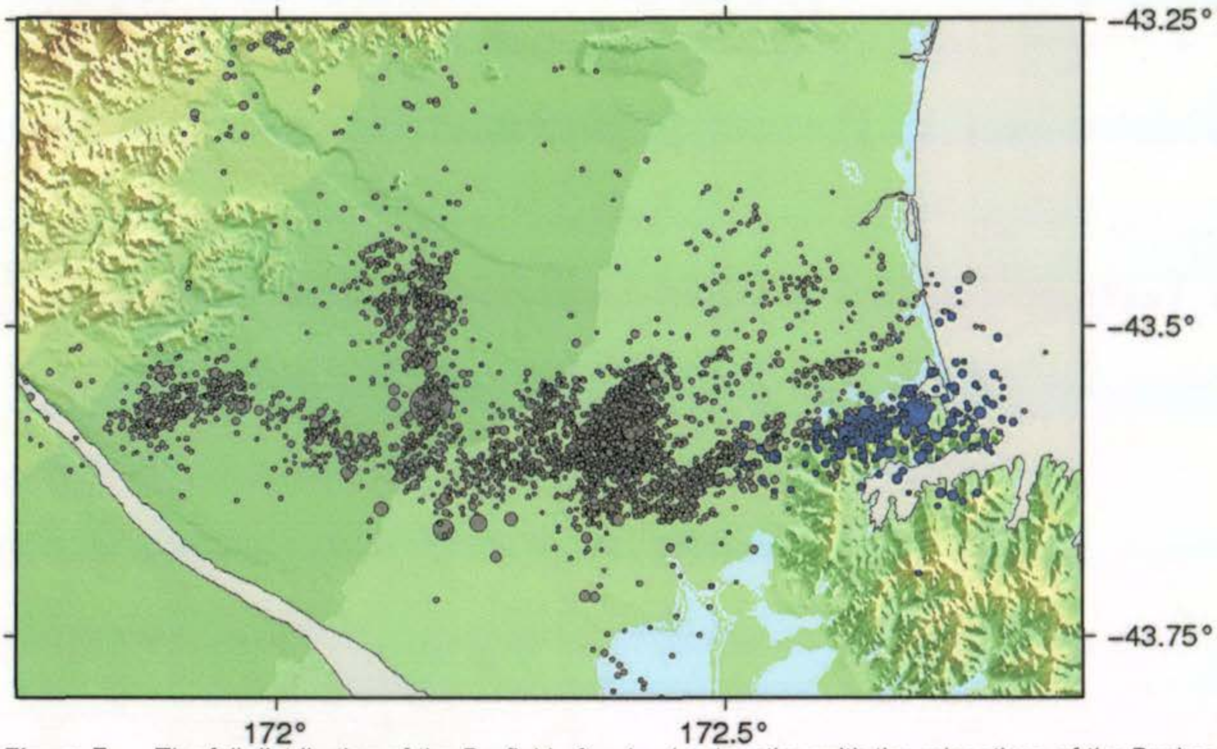

Figure 7 The full distribution of the Darfield aftershocks, together with the relocations of the Boxing Day sequence, as well as the first week of aftershocks following the February 22nd M6.3 earthquake (shown in blue). The Boxing Day sequence is the small cluster of events immediately (~ 4 km) to the north of the February aftershocks.

3.0 REFERENCES

Averym H.R., J.B.Berrill, P.F.Coursey, B.L.Deam, M.B.Dewe, C.C.Francois, J.R.Pettinga, and M.D.Yetton, 2004. The Canterbury University strong-motion recording project. *13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada. Paper 1335.*

Beavan, J., S. Samsonov, M. Motagh, L. Wallace, S. Ellis and N. Palmer, 2010. The M_w 7.1 Darfield (Canterbury) earthquake: geodetic observations and preliminary source model. *Bulletin of the New Zealand Society for Earthquake Engineering* 43, 228-235.

Du, W., C.H.Thurber and D. Eberhart-Phillips , 2004. Earthquake relocation using cross-correlation time delay estimates verified with the bispectrum method. *Bull. Seism. Soc. Am.*, 94, 856-866.

Eberhart-Phillips, D., M. Reyners, S. Bannister, M. Chadwick and S. Ellis, 2010. *Seismological Research Letters*, 81, 6, 992-1000. doi:10.1785/gssrl.81.6.992

Eberhart-Phillips et al, 2010; SRL 81:6, Electronic Supplement to Eberhart-Phillips et al., Internet web address : http://www.seismosoc.org/publications/srl/SRL_81/srl_81-6_eberhart-phillips_et_al-esupp/index.html (last accessed 16th February 2011)

GeoNet moment tensor data repository, 2011. Web reference : http://www.geonet.org.nz/resources/earthquake/ (last accessed 16th February 2011)

Gledhill, K., J. Ristau, M. Reyners, B. Fry and C. Holden, 2011. The Darfield (Canterbury, New Zealand) Mw 7.1 earthquake of September 2010: A preliminary seismological report. *Seismological Research Letters*, accepted.

Paige, C. and M. Saunders, 1982. An algorithm for sparse linear equations and least squares problems. *Trans.Math.Software*, 8, 43-71.

Petersen, T., K. Gledhill, M. Chadwick, N. Gale and J. Ristau, 2011. The New Zealand national seismograph network. *Seismological Research Letters*, 82, 9-20.

Python web reference, 2011. Python_mlab routines used in velocity field interpolation are described in http://code.enthought.com/projects/mayavi/docs/development/html/mayavi/mlab_pipeline_reference.html (last accessed 16th February 2011).

Quigley M., R. Van Dissen, P. Villamor, N. Litchfield, D. Barrell, K. Furlong, T. Stahl, B. Duffy, E. Bilderback, D. Noble, D. Townsend, J. Begg, R. Jongens, W. Ries, J. Claridge, A. Klahn, H. Mackenzie, A. Smith, S. Hornblow, R. Nicol, S. Cox, R. Langridge, and K. Pedley (2010). Surface rupture of the Greendale fault during the M_w 7.1 Darfield (Canterbury) earthquake, New Zealand: initial findings. *Bulletin of the New Zealand Society for Earthquake Engineering* **43. 236-242.**

Waldhauser, F., and W. L. Ellsworth, 2000. A double-difference earthquake location algorithmL Method and application to the northern Hayward fault, California, *Bull. Seismic. Soc. Am.*, 90, 1353-1368.

Zhang, H., C. Thurber and P. Bedrosian, 2009. Joint inversion for Vp, Vs, and Vp/Vs at SAFOD, Parkfield, California. *Geochemistry, Geophysics Geosystems*, 10, 1, Q11002.

GNS SCIENCE
TE PŪ AO

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
Lower Hutt 5010
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Dunedin 9016
Private Bag 1930
Dunedin 9054
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road, Wairakei
Taupo 3377
Private Bag 2000
Taupo 3352
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road, Gracefield
Lower Hutt 5010
PO Box 31312
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4657