Darfield Earthquake Geodetic Investigations

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The data presented in this Report are available to GNS Science for other use from 1 July 2011.

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EXECUTIVE SUMMARY

The geodetic survey network in the Canterbury region was significantly affected by displacements of up to ±2 metres caused by the 4 September 2010 Darfield earthquake. Land Information New Zealand (LINZ) requested GNS Science (GNS) to undertake dislocation modelling of the earthquake, in order to derive a model of fault geometry and fault slip that best fitted ground displacements observed by Global Positioning System (GPS) and Differential Interferometric Synthetic Aperture (DInSAR) techniques. The predictions of the model would be used by LINZ as part of their procedures to update the geodetic and cadastral systems following the earthquake.

The project was split into five tasks:

1. Supply a set of observed displacements and estimated uncertainties at GPS stations.
2. Calculate and supply a dislocation model of the faulting based on a fit to GPS and differential InSAR data, from which surface displacements can be calculated using the Okada equations.
3. Supply a set of calculated displacements at the GPS stations and on a regular grid.
4. Quantify regions where the model is a poor fit to the data.
5. A report on the four tasks above.

This report details the completion of this work. Parts of Tasks 2 and 3, and all of Tasks 4 and 5, were significantly delayed by the occurrence of the 22 February 2011, 13 June 2011 and 23 December 2011 Christchurch earthquakes, which required the author to undertake urgent work on modelling of these earthquakes.

Preliminary dislocation modelling results from these three Christchurch earthquakes were transferred to LINZ as they became available, at no cost to this project. These can be considered as additional deliverables.

1.0 INTRODUCTION

The 4 September 2010 Darfield (Canterbury) earthquake resulted in up to 5 metres of lateral slip along the previously unknown Greendale Fault (Figure 1) and associated ground surface displacements of up to about 2.5 metres within the surrounding region (Quigley et al., 2010, 2012; Beavan et al., 2010).

Land Information New Zealand (LINZ) requires a way to correct and update the survey system for the effects of the earthquake. One approach to this is to create a dislocation model of the earthquake that defines the fault surface(s) that ruptured in the earthquake and the distribution of slip on each fault surface. Such a model is designed to best fit available coseismic ground displacement data. The model may then be used to “predict” the displacement at other sites not included in the modelled ground displacement data set. If displacement observations exist at other sites not included in the modelled ground displacement data set, then a comparison between the predictions and observations at these sites can be used as one assessment of the quality of the model.

The project was split into five tasks, as follows.

Task Number	Description of Task
1	Supply a set of observed displacements and estimated uncertainties at GPS stations.
1a	Supply rinex data and field log sheets for stations observed by GNS.
1b	Process stations observed by GNS.
1c	Process stations observed by LINZ contractors in October 2010.
1d	Recalculate deformation model using campaign GPS data processed in IGS05, and thus a revised set of transformation parameters from IGS05 at epoch to NZGD2000 (because there are discrepancies between the MQZG displacement estimated from the GeoNet time series and the MQZG displacement calculated using the PONL-02 transformation.)
1e	Estimate coseismic displacements and uncertainties allowing for the national deformation model.
2	Calculate and supply a dislocation model of the faulting based on a fit to GPS and differential InSAR data, from which surface displacements can be calculated using the Okada equations.
2a	Supply a preliminary model as it becomes available.
2b	Supply two models at final delivery: one a best fit to the combined GPS and DInSAR data, the other a best fit to the GPS data alone.
3	Supply a set of calculated displacements at the GPS stations and on a regular grid.
4	Quantify regions where the model is a poor fit to the data. For example, this may be done by identifying regions where the predictions of the GPS and GPS+DInSAR models differ significantly.
5	A report on the four tasks above.

This report describes the completion of these tasks. Tasks 1a,b,c,e are discussed in Section 2; Task 1d in Appendix A; Tasks 2 and 3 in Section 3; and Task 4 in Section 4.

2.0 OBSERVED DISPLACEMENTS AT GPS SITES

2.1 RINEX data and field logs for GPS survey campaigns

Following the Darfield earthquake, GNS led three field campaigns to collect survey-mode GPS data. The sites we occupied are shown in Figure 1. In the first stage from 7-13 September 2010 we measured 80 sites within ~80 km of the earthquake in order to determine the coseismic (and a few days of postseismic) ground surface displacement field.

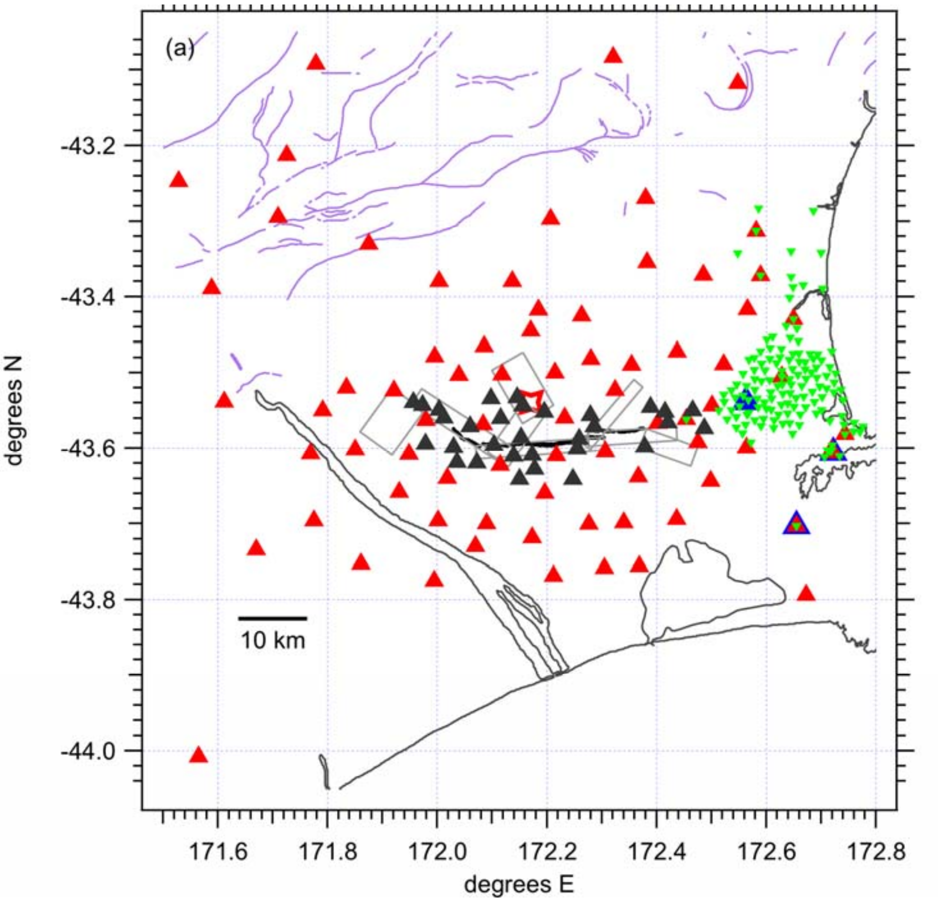


Figure 1 GPS sites occupied following Darfield earthquake. Blue triangles show cGPS sites; red triangles were occupied by GNS surveys; inverted green triangles were observed in the October 2010 LINZ survey; dark grey triangles were observed in the May 2011 LINZ survey. Magenta lines show mapped active faults, the heavy black line shows the mapped surface rupture of the Greendale Fault, and the light grey rectangles show the outlines of the model fault planes.

We occupied a mix of sites that had high-quality pre-existing GPS observations within the past 2-3 years, and "3rd-order" sites with Land Information New Zealand (LINZ) Geodetic Database coordinates that had been calculated from GPS data collected more than 10 years ago. At the 25 high-quality stations, we collected several 24 hour sessions of GPS data. At the 55 lower-quality stations, we collected at least one 24-hour session at five sites and one to several hours of data at the other 50. Seven of the latter stations were in the middle of roads, and data from these were collected using kinematic techniques with post-processing.

In the second stage from 27-30 September we reoccupied 45 of the sites closer to the earthquake and measured two additional sites, with sessions of at least 2 hours at the lower-quality sites and at least one session of 24 hours at five of the high quality stations. The intention was to see if a significant amount of postseismic displacement (afterslip or poroelastic effects) had taken place in the period between 1 and 3 weeks after the earthquake. We also measured longer sessions at three of the lower-quality stations in order to provide higher quality coordinates at these sites for future studies of longer-term postseismic deformation.

In the third stage from 26-29 October we occupied an additional 12 of the lower-quality sites with a 24-hour session, again to provide data for future post-seismic studies.

The RINEX data and field logs for these three campaigns are included on the CD accompanying this report.

2.2 GPS processing, additional surveys, and coseismic displacements

We processed the GPS data using standard techniques (e.g., Beavan et al., 2010a; Section A1 of Appendix A) to provide post-earthquake coordinates for the sites. These coordinates were placed in the IGS05 reference frame at the current epoch by applying a Helmert transformation onto the IGS05 coordinates of a set of Australian and Pacific IGS sites at the final stage of each day's processing (Figure A1). Because we only have the originally-calculated LINZ NZGD2000 coordinates for the lower-quality sites, we transformed the post-earthquake coordinates to their NZGD2000 values using transformation parameters calculated as described in Appendix A (see also the PONL-02 report by Beavan, 2008). This transformation takes account of the ongoing plate boundary deformation and the difference in international terrestrial reference frames between the current frame (ITRF2005) and the one used for NZGD2000 (ITRF96). We then subtracted the two sets of NZGD2000 coordinates from each other to give the east, north and up displacements at these sites. We estimated the displacements at the high-quality stations by a similar method. We transformed both the post-earthquake coordinates and the most recent high-quality pre-earthquake coordinates to NZGD2000 and took their differences to give the estimated coseismic displacements. We assigned uncertainties to the displacements based on whether they were estimated from two sets of low-quality coordinates, two sets of high-quality coordinates, or one of each. We also estimated the coseismic displacements at stations in the GeoNet and LINZ continuous GPS (cGPS) networks. We averaged coordinates in the regionally-filtered GeoNet time series for several days before and after the earthquake, and took their difference. The largest displacement at a cGPS site was ~140 mm at McQueen's Valley (MQZG) south of Christchurch. Detectable displacements were observed at another 6 cGPS stations: Lyttelton, Lake Taylor, Kaikoura, Westport, Hokitika and Waimate. Figure 2(a) shows the GPS horizontal displacement vectors and Figure 3 the vertical displacements.

In addition to the GNS-led surveys, LINZ commissioned a survey from 11-21 October 2010 (Figure 1). This was principally to observe sites in Christchurch City using fast-static techniques, but also included some longer-occupations sites that we processed at GNS. This survey was processed by Nic Donnelly at LINZ, constraining the coordinates of sites 5508, MQZG and B87X to match their coordinates derived by the GNS processing. The coseismic displacements were derived in a way similar to that used by GNS, and the resulting displacements were incorporated into our modelling of the earthquake.

Because we did not detect significant post-seismic deformation (a few tens of mm at most) at any GPS site between our first and third post-earthquake surveys, we combined the data from all these post-earthquake surveys in our modelling of the earthquake, without any correction for post-seismic deformation.

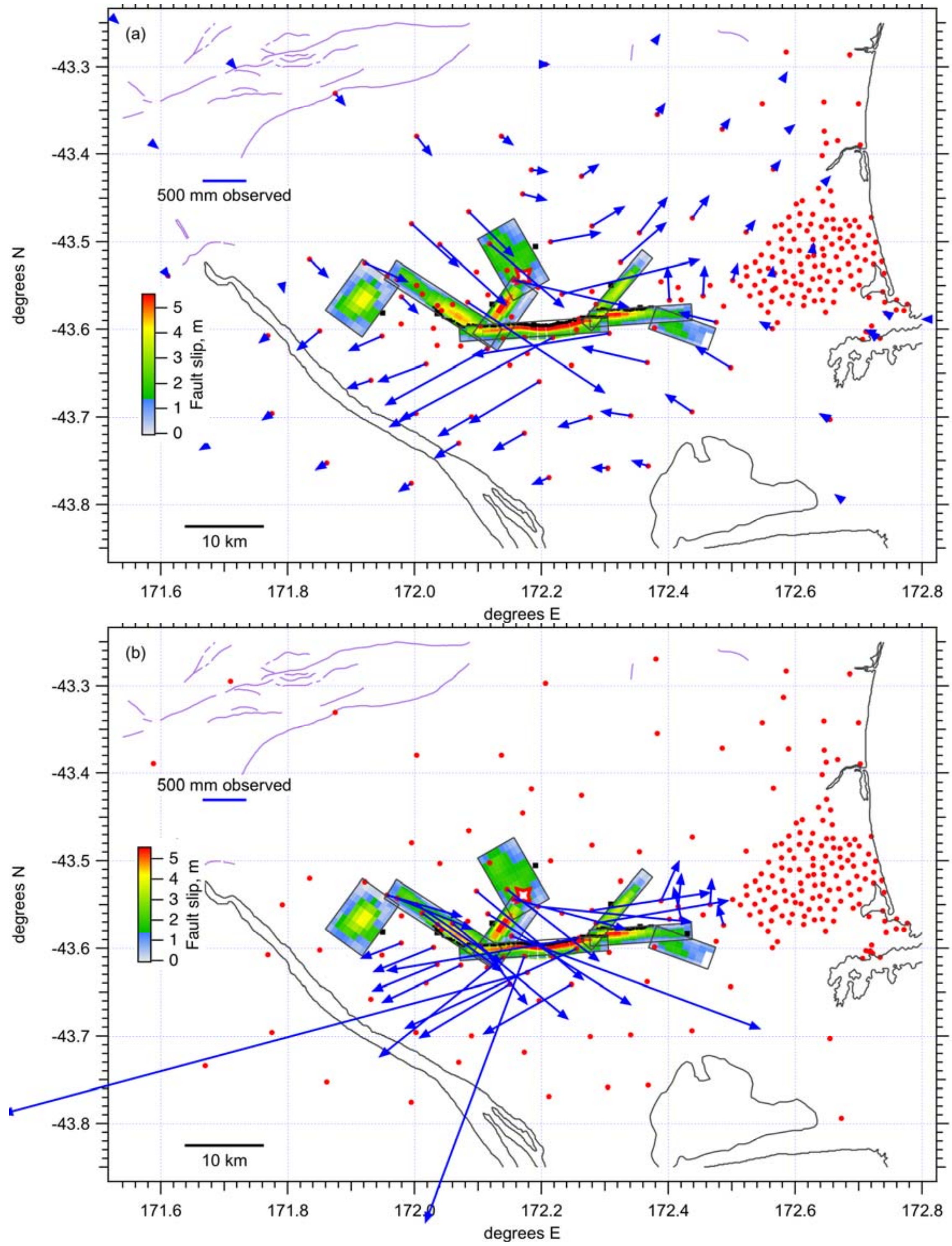


Figure 2 (a) Observed displacements at the sites occupied in the GNS-led surveys. For clarity, uncertainty ellipses are not shown. The model fault slip and geometry (see Section 3) are shown by the coloured images. Red dots show GPS sites observed by GNS and LINZ. Red-and-white four-pointed star shows the epicentre of the Darfield earthquake. Magenta lines show active faults. (b) Observed displacements at the 5th-order sites occupied in the LINZ May 2011 survey. These are used as a quality-control check on the model.

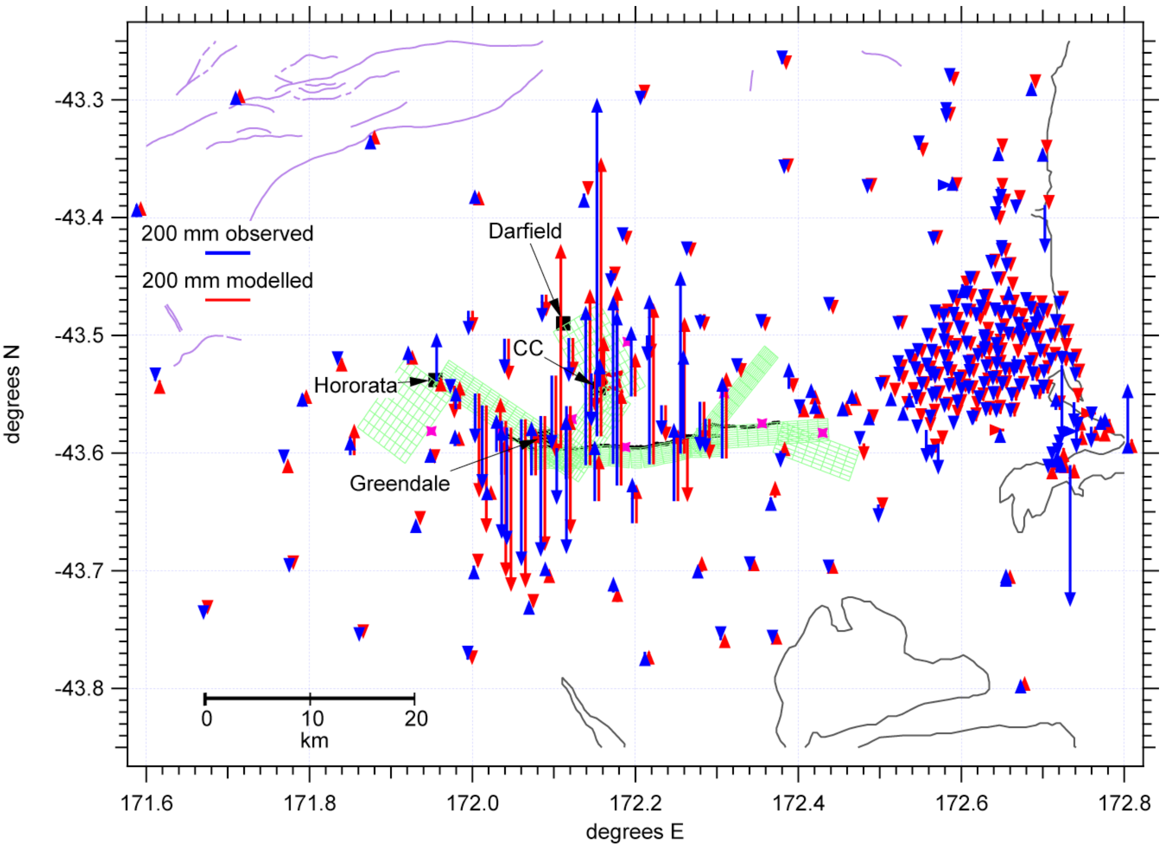


Figure 3 Observed (blue) and modelled (red) vertical displacements at the sites occupied in the GNS and LINZ surveys. For clarity, uncertainty ellipses are not shown. The model fault geometry (see Section 3) is shown by the light green rectangles. Red-and-white four-pointed star shows the epicentre of the Darfield earthquake. Magenta lines show active faults.

LINZ also commissioned a survey from 11-12 May 2011 in the vicinity of the Darfield earthquake, to measure the coseismic displacements at a number of 5th-order sites not occupied by GNS (Figure 1). We did not include these in our modelling of the earthquake, preferring to use them as a quality check on the model by comparing the observed displacements, shown in Figure 2(b), with the model predictions.

The estimated coseismic displacements for stations observed in these various surveys are provided as an Excel spreadsheet in Table CD1 on the accompanying CD.

3.0 DISLOCATION MODELS AND CALCULATED DISPLACEMENTS

Information about geological and seismological aspects of the Darfield earthquake can be found in a number of publications (e.g., Quigley et al., 2010, 2012; Gledhill et al., 2011). Dislocation modelling of the earthquake has been described in several publications (Beavan et al., 2010b, 2012; Elliot et al., 2012). The model delivered with this report is a modified version of the one described in Beavan et al. (2012), to which we refer the reader for details of the modelling. The modifications are: (1) we have included in the model the Christchurch City GPS data collected by LINZ contractors in October 2010; (2) we have added an additional fault plane at the eastern end of the model in order to better fit GPS data; (3) we have weighted the GPS data a factor of ~30% higher than the Differential Interferometric Synthetic Aperture Radar (DInSAR) data, in order to favour the GPS data over the DInSAR.

The model (which we refer to as v8.5) is shown in Figure 4 and is provided as an Excel spreadsheet in Table CD2 on the accompanying CD. (It is also provided in a slightly different format as "Darfield_geodetic_source_model_8.5.xls".) The model predictions, and residuals between the observations and model, are given in Table CD1. Predictions of the model at a grid of points covering the whole region are given at 0.5 km spacing in Table CD3, and for the Christchurch region at 0.25 km spacing in Table CD4. Figure 5 shows contours of vertical displacement derived from the model values in Tables CD3 and CD4.

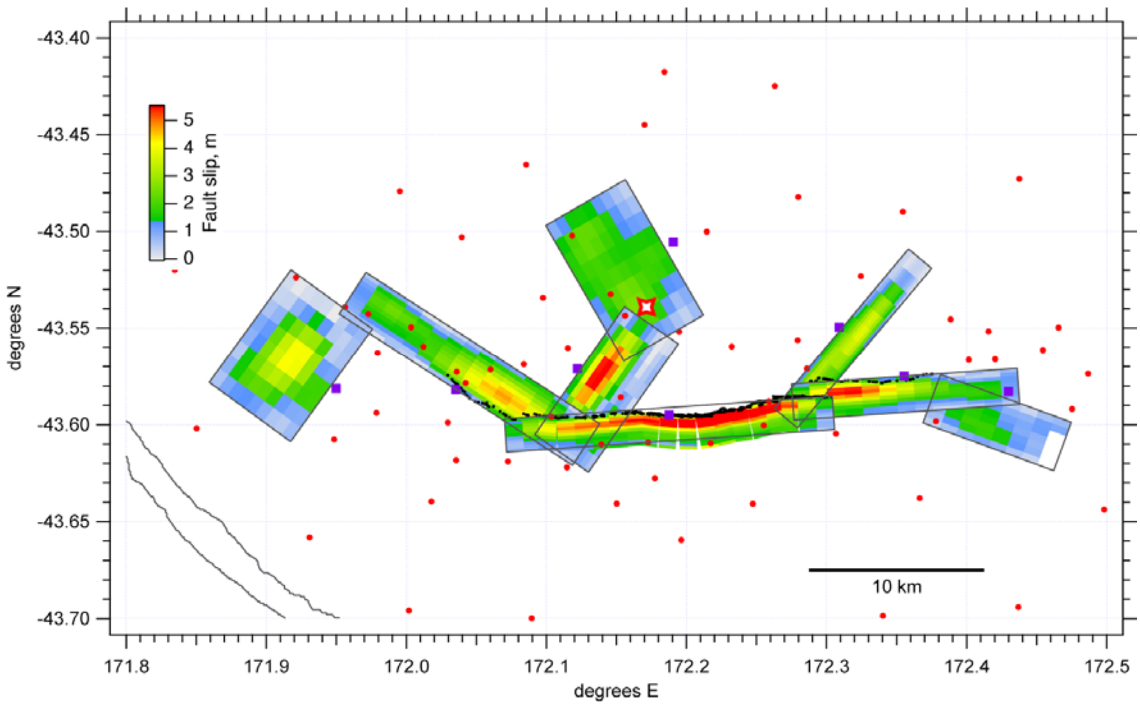
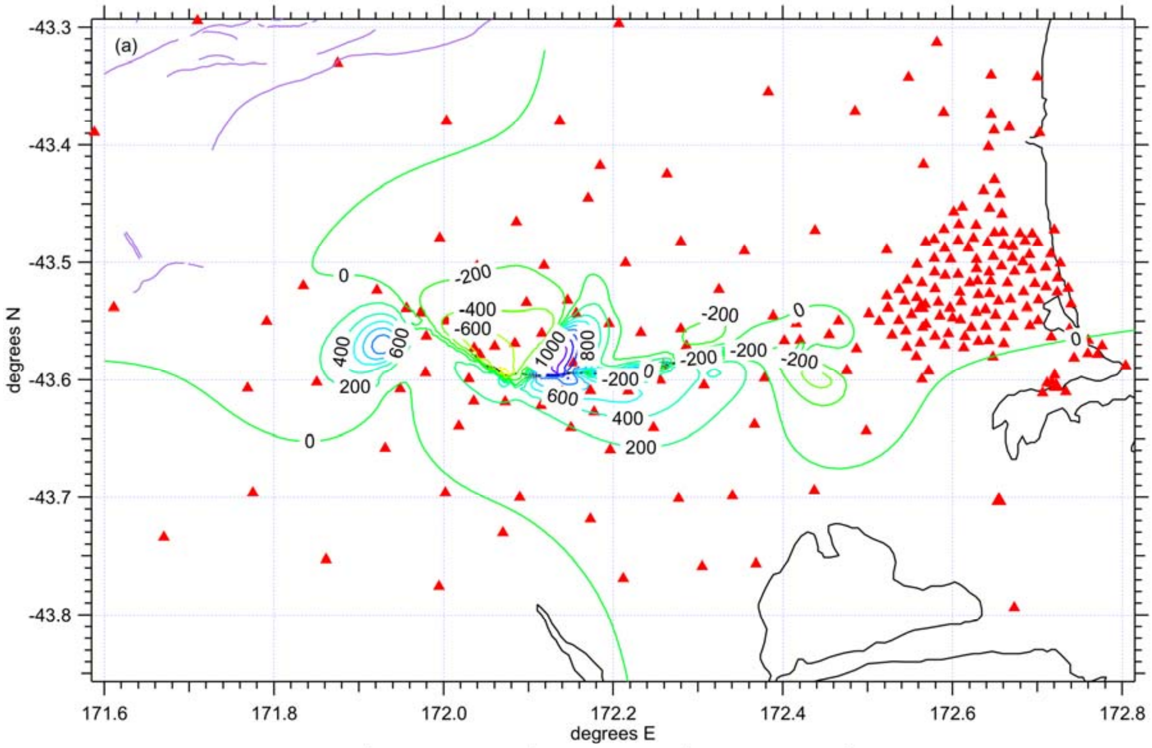


Figure 4 Geometry and slip distribution of dislocation model v8.5. The Greendale Fault surface rupture is shown by the black line. Each large rectangle shows a separate fault plane in the model, and each cell within these planes measures 1×1 km. The slip magnitude within each fault plane is shown by the coloured images. Slip reaches more than 6 m on the central section of the Greendale Fault. Purple squares indicate the point at which the centre of the fault segment would outcrop if it were extended to the surface; these therefore indicate the top edge of each fault segment. The model for the central section of the Greendale Fault is not rectangular but has been modified to more closely follow the surface rupture of the fault. Red dots show GPS sites. Red-and-white four-pointed star shows the epicentre.

In the modelling, we have strongly downweighted GPS displacement data from 11 points in the October 2010 data set (see Table CD1), because their residuals are highly inconsistent with nearby points. We believe these anomalies are probably due to liquefaction or lateral spreading in Christchurch. We have done the downweighting somewhat subjectively, but we do not believe any errors in our downweighting will have a significant effect on the model, because there are so many nearby points in Christchurch that do fit the model well.

There are also a number of sites with high residuals in the GNS data set (Table CD1), but we have chosen not to downweight these data as there is no obvious ground failure at any of these sites.

The faulting pattern is so complex (and hence the number of model parameters is so large) that obtaining a best-fit model by conventional optimisation techniques is not possible. We have obtained a good fit to observed GPS and DInSAR ground displacement data by means of a mix of grid search and optimisation, and by constraining model faults to surface ruptures where these were found. However, we cannot claim this is the best possible model.



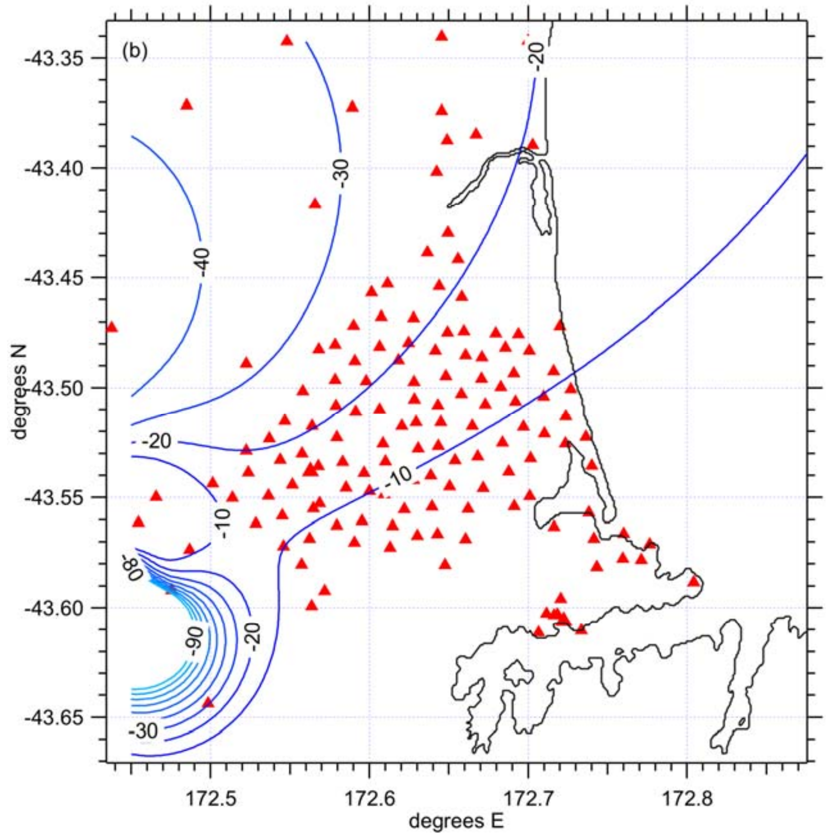


Figure 5 Contours of vertical displacement in mm predicted by the v8.5 dislocation model. Red triangles are GPS stations. Magenta lines are active faults mapped prior to the Darfield earthquake. (a) shows contours over the wider region, and (b) shows contours over Christchurch. The model predicts subsidence of 0-30 mm within the city.

In Table CD1 we provide the residuals between the observed and modelled displacements, both as the residuals and as the standardised residuals (residuals divided by data standard errors). These are discussed further in Section 4.

4.0 TESTS OF MODEL ACCURACY

We consider that the best way to assess model quality is to compare the model predictions with the observed displacements at the LINZ sites observed in May 2011. These sites (Figure 1) surround the Greendale Fault region, and are independent data as they were not included in the modelling. Table CD1 gives the values of the residuals (= observed-model), and the standardised residuals (= (observed-model)/σ_{obs}, where σ_{obs} is the standard error of the observed data). Figure 6 plots the residuals at both the modelled points and the "quality-control" points.

Table 1 summarises the residuals listed in Table CD1. The table gives the RMS of both the residuals and the standardised residuals for each of the east, north and up components. These statistics are compiled separately for the cGPS displacements, and for displacements measured in the GNS-led surveys, the LINZ October 2010 survey and the LINZ May 2011 survey. For the LINZ October 2010 survey, 11 points with particularly large residuals have been omitted from the statistics (and strongly downweighted in the modelling). Two points (DBQ2 and DBQ3) with very large residuals (>2.3 m) have similarly been omitted from the LINZ May 2011 statistics.

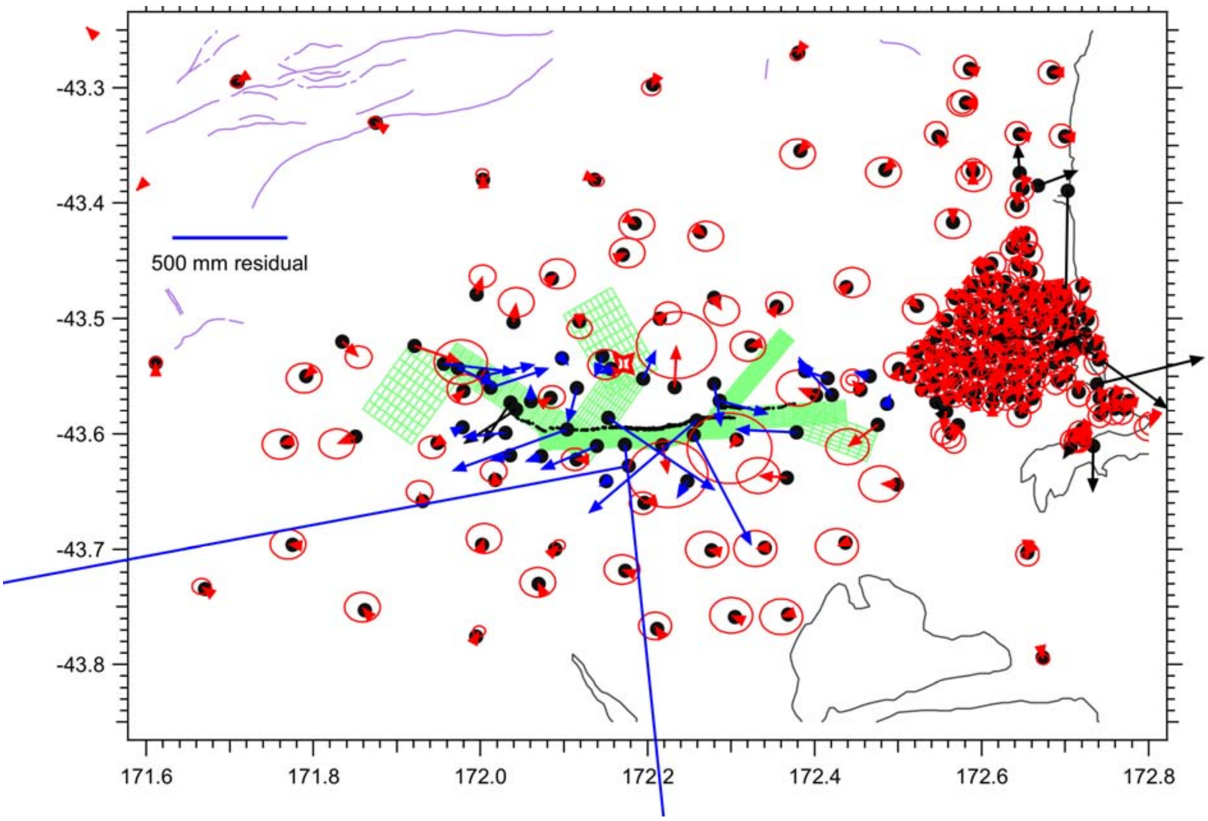


Figure 6 Residuals between observations and model. Red vectors with uncertainty ellipses show the residuals at sites used at normal weighting in the model. Black vectors show the residuals at sites used but strongly downweighted in the model. Blue vectors show the residuals at the "quality-control" sites observed in May 2011.

Table 1 RMS (mm) of residuals between observations and model fit for the various surveys

	cGPS	GNS	LINZ 2010	LINZ 2011	LINZ 2011 less 4
No. of sites	6	87	125	29	25
			Residuals		
East, mm	4.0	36.3	10.9	212.6	147.4
North, mm	4.6	34.9	13.5	145.1	79.9
Up, mm	7.6	38.1	29.1	263.7	91.2
			Standardised residuals		
East, mm	1.0	1.1	0.5	7.1	4.9
North, mm	1.8	1.4	0.7	4.8	2.7
Up, mm	0.7	0.5	0.9	5.3	1.8

Table 2 RMS (mm) of residuals between observations and model fit for points more than ~1 km from a model fault plane

	GNS	LINZ 2011
No. of sites	78	13
	Residuals	
East, mm	25	63.6
North, mm	30.5	73.1
Up, mm	37.2	55.9
	Standardised residuals	
East, mm	1.0	2.1
North, mm	1.4	2.4
Up, mm	0.5	1.1

The most appropriate comparison for quality checking is between the GNS statistics and the LINZ 2011 statistics. This is because these surveys each observed sites in the vicinity of the Greendale Fault where the largest coseismic displacements occurred. Looking at either the residuals or the standardised residuals, the LINZ 2011 results are approximately a factor of 5 larger than the GNS results. The GNS residuals for site displacements included in the model are approximately 35-40 mm, while the LINZ residuals for site displacements not included in the model are approximately 150-250 mm. These latter values give an indication of the true quality of the model in the vicinity of the Greendale Fault.

However, several sites very close to the fault (BQAA, DBQM, DBQN, DBR9) have substantially larger residuals (>0.5 m) than others (Figure 6). It can be argued that these four should be omitted from the statistics, on the basis that minor changes in fault geometry could dramatically improve their fit. If this is done (Table 1, final column), the quality-control residuals fall by about a factor of two and indicate that the model fits the quality-control data at a level of 80-150 mm.

We can also split the data into points that lie close to a model fault plane and those that are further away. Table 2 repeats Table 1 for the GNS and LINZ 2011 surveys, selecting only points that lie more than ~1 km from any fault plane.

This does not make a major difference to the statistics for the points that were fitted to the GNS surveys included in the model, but it reduces the RMS of the residuals at the quality-check sites to 50-80 mm. This suggests that the quality of fit to the non-modelled sites is only a factor of two worse than the fit to the modelled sites, at points more than ~1 km from any of the modelled fault planes. Some of this difference may be due to the fact that the quality-control sites are 5^{th} order, so they have less accurate coordinates than those observed in the GNS surveys.

5.0 RECOMMENDED FUTURE WORK

An additional check of the model could be made by comparing its predictions with results of the Canterbury levelling commissioned by LINZ since the Darfield earthquake.

Other high-quality dislocation models of the Darfield earthquake have been published (Elliot et al., 2012) or are nearing publication, based on DInSAR data alone. If these models were made available by their authors, it would be possible to test whether they provided a better or worse fit than the model supplied with this report, both at stations used in modelling and at LINZ quality-control stations.

Additional “tweaking” of the model could be attempted in order to better fit the observed data, and additional satellite radar images could be added to the modelling. However, it is possible that we have already reached a point of diminishing returns in improving the model.

6.0 CONCLUSIONS

A dislocation model consisting of eight separate fault segments has been generated that provides a good fit to coseismic ground surface displacements observed by GPS and DInSAR at the time of the 4 September 2010 Darfield earthquake. Six of the eight fault segments are clearly required by the data, and are closely confirmed by independent modelling (Elliot et al., 2012). The evidence for the two segments near the eastern end of the Greendale Fault is less convincing, but their presence provides clear improvement to the fit of the model to GPS displacement data.

The model predictions are generally accurate at sites more than ~1 km from the model faults (excluding a few sites affected by ground failure such as liquefaction or lateral spreading), as judged by comparing observed and predicted displacements at points not included in the modelling. The model predictions were compared with observed displacements at 31 “quality-control” sites. Two of these were discarded because their residuals were greater than 2.3 m (suggesting blunders or ground failure at these sites). The other quality-control sites were fit at a level of 150-250 mm. Four of these sites located very close to the Greendale Fault surface rupture have residuals greater than 0.5 m. If these are removed, on the grounds that modest changes to the fault geometry could substantially change their residuals, the fit at the remaining 25 quality-control sites improves to 80-150 mm. If we further omit sites within ~1 km of any model fault plane, the fit to the remaining 13 sites improves to 50-80 mm. This compares well with the 30-40 mm fit to points included in the modelling, especially when it is considered that the coordinates of the quality-control sites were only determined to 5th order.

7.0 ACKNOWLEDGEMENTS

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8.0 REFERENCES

Altamimi, Z., X. Collilieux, J. Legrand, B. Garayt and C. Boucher, 2007. ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters, J. Geophys. Res., 112, B09401. doi:10.1029/2007JB004949

Beavan, R. J., 1998. Revised horizontal velocity model for the New Zealand geodetic datum, Client Report 43865B for Land Information New Zealand, GNS Science, Lower Hutt, 46 pp., November 1998.

Beavan, J., 2005. Noise Properties of Continuous GPS Data From Concrete-Pillar Geodetic Monuments in New Zealand, and Comparison With Data From U.S. Deep Drilled Braced Monuments, J. Geophys. Res., 110(B8), B08410, doi:10.1029/2005JB003642.

Beavan, R. J., 2008. Consultancy services for coordinates for PositioNZonLine, Phase 2 (PONL-02), Consultancy Report 2008/136 for Land Information New Zealand, GNS Science, Lower Hutt, 79 pp, June 2008.

Beavan J., S. Samsonov, P. Denys, R. Sutherland, N. Palmer and M. Denham, 2010a. Oblique slip on the Puysegur subduction interface in the 2009 July M_W 7.8 Dusky Sound earthquake from GPS and InSAR observations: implications for the tectonics of southwestern New Zealand. Geophys. J. Int., 183(3), 1265-1286. doi: 10.1111/j.1365-246X.2010.04798.x

Beavan J., S. Samsonov, M. Motagh, L. Wallace, S. Ellis and N. Palmer, 2010b. The Darfield (Canterbury) earthquake: geodetic observations and preliminary source model. Bulletin of the New Zealand Society for Earthquake Engineering 43(4): 228-235.

Beavan J., M. Motagh, E. Fielding, N. Donnelly and D. Collett, 2012. Fault slip models of the 2010-2011 Canterbury, New Zealand, earthquakes from geodetic data, and observations of post-seismic ground deformation, N. Z. J. Geol. Geophys., in press.

Bibby, H. M., 1982. Unbiased estimate of strain from triangulation data using the method of simultaneous reduction, Tectonophysics, 82(1-2), 161-174.

Crook, C. N., 1992. ADJCOORD: a Fortran program for survey adjustment and deformation modelling, NZ Geol. Surv. Earth Def. Sec. Report, 138, Dept. Sci. Indust. Res., Lower Hutt, N. Z., 22 pp.

Dach, R., U. Hugentobler, P. Fridez and M Meindl (eds.), 2007. Bernese GPS Software Version 5.0, Astronomical Institute, University of Berne, Berne, Switzerland, January 2007.

Elliot J. R., E. K. Nissen, P. C. England, J. A. Jackson, S. Lamb S, Z. Li, M. Oehlers and B. Parsons, 2012. Slip in the 2010-2011 Canterbury earthquakes, New Zealand. Journal of Geophysical Research, 117: B03401. doi:03410.01029/02011jb008868

Gledhill K., J. Ristau, M. Reyners, B. Fry and C. Holden, 2011. The Darfield (Canterbury, New Zealand) M_W 7.1 earthquake of September 2010: A preliminary seismological report. Seismological Research Letters 82(3): 378-386. doi: 10.1785/gssrl.82.3.378

Quigley M., P. Villamor, K. Furlong, J. Beavan, R. Van Dissen, N. Litchfield, T. Stahl, B. Duffy, E. Bilderback, D. Noble, D. Barrell, R. Jongens and S. Cox, 2010. Previously unknown fault shakes New Zealand's South Island. EOS, Transactions American Geophysical Union 91: 469-472.

Quigley M., R. Van Dissen, N. Litchfield, P. Villamor, B. Duffy, D. Barrell, K. Furlong, T. Stahl, E. Bilderback and D. Noble, 2012. Surface rupture during the 2010 M_W 7.1 Darfield (Canterbury) earthquake: implications for fault rupture dynamics and seismic-hazard analysis, Geology 40(1): 4p.

Wallace, L. M. and J. Beavan, 2010. Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand, J. Geophys. Res., 115, B12402, doi:10.1029/2010JB007717.

Williams, S. D. P., 2003. The effect of coloured noise on the uncertainties of rates estimated from geodetic time series, J. Geodesy, 76, 438-494.

Williams, S. D. P., Y. Bock, P. Fang, P. Jamason, R. Nikolaidis, L. Prawirodirdjo, M. Miller, and D. Johnson, 2004. Error analysis of continuous GPS position time series, J. Geophys. Res., 109, B03412. doi:10.1029/2003/JB002741

APPENDICES

APPENDIX A UPDATED DEFORMATION MODEL

In this Appendix we discuss the creation of an updated (v4.0) deformation model, and updated transformation parameters between the IGS05 and NZGD2000 reference frames. These parameters and deformation model were used to account for interseismic deformation in the period between pre-earthquake and post-earthquake surveys (as discussed in Section 2 above for the Darfield earthquake), and to generate post-earthquake NZGD2000 coordinates for stations that were used as control stations for lower-order surveys carried out following the various Christchurch earthquakes.

A1 Reprocessing of survey-mode GPS data collected from 1996 to 2011

We have reprocessed all survey-mode GPS data collected in New Zealand between January 1996 and February 2011. We used a minimum session length of 6 hours, because many survey-mode data were collected in 6-8 hour sessions, especially in earlier years. Some data collected across day boundaries in 1996 are omitted from the processing under this procedure. The GPS phase data from each session were processed in a network solution using the high-accuracy Bernese version 5.0 processing package (Dach et al., 2007), to determine daily estimates of relative coordinates and their covariance matrices. The IGS_01 elevation-dependent antenna phase-centre models were used to account for the different antennas used. Zephyr Geodetic antennas were used at all New Zealand sites except CHAT to further minimise any problems associated with antenna mixing. (Zephyr Geodetic II antennas were used in later years at a few cGPS stations included in the campaign processing.) We included estimates of ocean load displacement in the analysis, using the TPX0.7.1 ocean tide model and the on-line ocean loading calculator from Onsala Space Observatory (http://www.oso.chalmers.se/~loading). Tropospheric delays were estimated hourly at each station in a piecewise continuous fashion, and the tropospheric gradient was estimated daily in a piecewise continuous fashion. The dry Niell model was used as the a priori model, with the wet Niell mapping function used to map slant-path delays to zenith.

During each day's processing, IGS final orbits and associated polar motion files were held fixed. The IGS final orbits were generated in a variety of reference frames, as later realisations of the ITRF were adopted by the IGS. For all orbits prior to the adoption of ITRF2000 we have transformed the orbit and polar motion files to ITRF2000 using the transformation parameters published by the IERS. If there are regional distortions in any of the reference frames, these will not be corrected by this procedure. At the last stage of the Bernese processing, we applied a 3-parameter Helmert transformation (3 translations) to the coordinate results so as to best fit the ITRF2005 (IGS05 realisation) coordinates of a set of regional IGS stations at the epoch of observation. The IGS stations used for reference frame realisation were: ALIC, CEDU, CHAT, DARW, HOB2, KARR, MCM4, NOUM, PERT, TIDB, YAR1/2 (see Figure A1). The daily coordinate results are therefore nominally in the ITRF2005 reference frame (IGS05 realisation) at the epoch of measurement. Insofar as the possible regional distortions referred to above can be described by a Helmert transformation, this procedure will tend to correct the distortion.

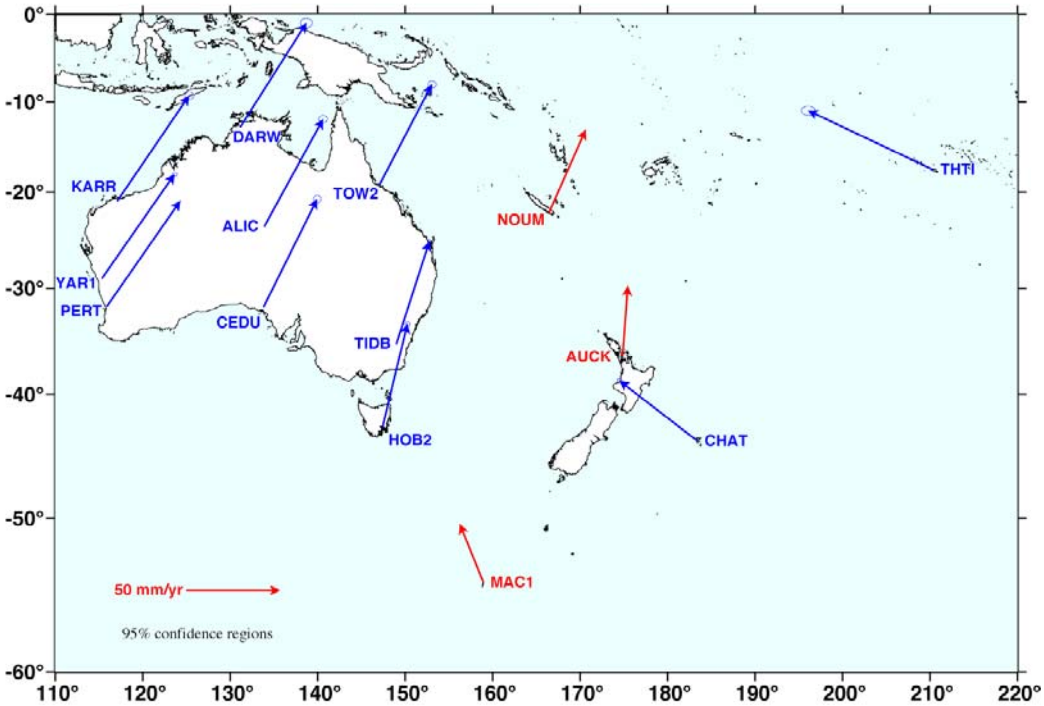

Figure A1 Regional IGS stations processed in our daily Bernese analysis, with their official IGS05 horizontal velocities (blue) and IGS05 velocities estimated by GNS (red). Station MCM4 (McMurdo Sound) is also used and would be shown in blue if it were on the map. We treat YAR1 and YAR2, which share an antenna, as the same station, and similarly for TIDB and TID2. Various subsets of these stations are used for reference frame realisation. In the VELFRAME analysis, the blue stations plus MCM4 are used as reference stations.

A1.1 Treatment of coseismic displacements from nearby earthquakes

Coseismic displacements due to several nearby earthquakes have caused significant displacements at sites in New Zealand. In order to obtain the best estimates of steady-state (interseismic) velocity we have made a correction to the daily coordinate data following the times of these earthquakes (Table A1) to all sites throughout New Zealand. These corrections are generally small except in the vicinity of the earthquake, though displacements from the 23 December 2004 M_w 8.0 Macquarie earthquake are detectable throughout the country.

These corrections were made prior to the adjcoord analysis, as described below.

1. For each of the earthquakes in Table A1, we correct the daily coordinate-difference data by subtracting the coseismic model prediction for each station in each daily data set later than the day of the earthquake. (In fact, because the data are now in the form of coordinate differences, we subtract the difference between the model predictions at the two stations). We do not modify the daily covariance matrices as we consider we are only making a small correction to the coordinate data.
2. We omit the data set collected in the several weeks following the 2003 earthquake. This is because any postseismic deformation due to afterslip is likely to be greatest in the several months following the earthquake. If left in the data set these data could bias the estimation of the steady velocity.
3. For sites close (approx. 100 km) to the 2003 earthquake we solve independently for the velocity before and after the earthquake. This is so that the site velocity is not biased by any inaccuracy in our coseismic correction. It also gives us the opportunity to investigate if there is a significant velocity change at the time of the earthquake.

4. We omit the data set collected about two months after the 15 October 2007 M_w 6.8 Fiordland earthquake because there is no later survey (prior to the 2009 Dusky Sound earthquake) that could contribute to a velocity solution.
5. We omit all South Island data following the 4 September 2010 Darfield earthquake.

Table A1 Model parameters for coseismic corrections

	Secy. Is. 21 Aug 2003	**Macquarie 23 Dec 2004**	**Fiordland 16 Oct 2007**	**Dusky Sound 15 Jul 2009**
Lat, º [1]	-45.13	-50.4	-44.8	Variable slip model. See Beavan et al. (2010a).
Lon, º	166.941	160.9	167.42	
Depth, km	19	11	20	
Strike, º	30	340	60	
Dip, º	30	90	41	
Rake, º	98	17	135	
Slip, m	4.3	5.1	2.74	
Length, km	35	300	12	
Width, km	12	20	17	
Mw	7.1	8.0	6.8	7.8
Poisson	0.25	0.25	0.25	0.25
Lat0, ° [2]	-45	-50.5	-45	-46
Lon0, °	167	161	167	166.5

[1] Lat, lon and depth describe the centre of the fault plane.
[2] Lat0 and lon0 are the origin used for converting geographic to Cartesian coordinates, using x = -(lat-lat0)×111.2 km south, y = (lon-lon0)×111.2 ×cos(lat0×pi/180) km east.

A1.2 Treatment of slow slip events beneath the North Island

Using these procedures we have corrected for biases in steady velocity estimation that would otherwise result from the occurrence of earthquakes in or near the GPS network. The occurrence of slow slip events (SSEs), or "slow earthquakes" affecting much of the southern and eastern North Island means that similar biases will be present in the calculated velocity field in the North Island (Wallace and Beavan, 2010).

For LINZ's purposes, the important requirement is that the deformation model should predict the horizontal site position to within 50 mm (and preferably substantially better than that). Concerning SSEs, the two end-member approaches are:

1. Use the average velocity as determined from the occasional survey-mode measurements. So long as the SSE amplitudes at the surface are fairly small (36 mm is the largest we have seen to date), and especially if the SSEs occur quite frequently (as they appear to do along the east coast), this estimated average velocity will give a fairly accurate prediction of future position (within 15-20 mm) even in the presence of SSEs. If some SSE displacements are much larger than 30 mm, or if the repeat interval is on the order of the length of the GPS data set, or longer, then it is possible that velocities

estimated from occasional survey-mode data will be substantially in error, thus leading to prediction errors that could exceed 50 mm.

2. Generate an inversion model that uses all continuous and campaign GPS time series to estimate the location, amplitude and duration of every SSE and earthquake as well as the velocity between these events. This is a more complex prediction tool than a simple position and velocity, and it is also not applicable to data prior to about 2002 when we started to gather information on SSEs.

For this report we keep to the first approach, but we note that the second approach could be considered by LINZ in the future. As the global earth science community learns more about SSEs over the next few years, the best approach to modelling them should become clearer.

A2 ADJCOORD processing of daily coordinate/covariance solutions

All daily coordinate-difference solutions and their covariances were input to the least squares adjustment software ADJCOORD (Crook, 1992; Bibby, 1982) to check for outliers and to obtain the appropriate χ^2 factor for subsequent scaling of the covariance matrix. The data set consists of about 1250 daily coordinate and covariance solutions from just over 16 years of data collection. Station AUCK was held fixed to obtain a minimally-constrained solution. The covariance matrices require scaling because the temporal correlation of the GPS phase data is neglected in the estimation of the formal errors in the Bernese software, so that the formal uncertainties are underestimated compared to the scatter in daily coordinate results. The scaling factor depends on the noise properties of each data set, and also depends on the sample interval of the GPS phase data used to obtain final coordinates. A factor of 5^2 (=25) was determined for the 180-second samples we use in the final stages of our processing (in which 30-second samples are used for data editing and cycle-slip fixing, then the data are decimated to 180 seconds for subsequent processing). This factor is consistent with what we have found for other regional GPS surveys. This procedure ensures that the relative coordinate uncertainties are consistent with the scatter of repeated observations within the survey. The standard error of unit weight of the solution was 1.17. An advantage of estimating the velocities this way, as opposed to directly estimating them relative to a global or regional reference frame, is that common-mode signals within New Zealand are removed to first order. A disadvantage is that the resulting velocity field has later to be transformed into some conventional reference frame.

The result of the adjcoord processing is a set of 920 velocities relative to AUCK from 911 sites in New Zealand (Figure A2) (9 sites in Fiordland and Southland have two velocity estimates each – one before and one after the 2003 earthquake), plus another 13 site velocities in Australia and the Pacific.

A3 VELFRAME processing of daily coordinate/covariance solutions

Coordinates and velocities for New Zealand stations in the IGS05 reference frame are generated by a filtering procedure where the daily coordinate/covariance solutions for the New Zealand stations and a set of IGS stations are added to the filter one daily solution at a time. The solutions are maintained in the required reference frame by transforming the daily coordinates using a (3- to 7-parameter) transformation that brings the coordinate solutions of a set of IGS stations as close as possible to their “official” ITRF values for that day. Specifically, we use the IGS05 realisation of ITRF2005 (Altamimi et al., 2007) to obtain a solution in that reference frame.

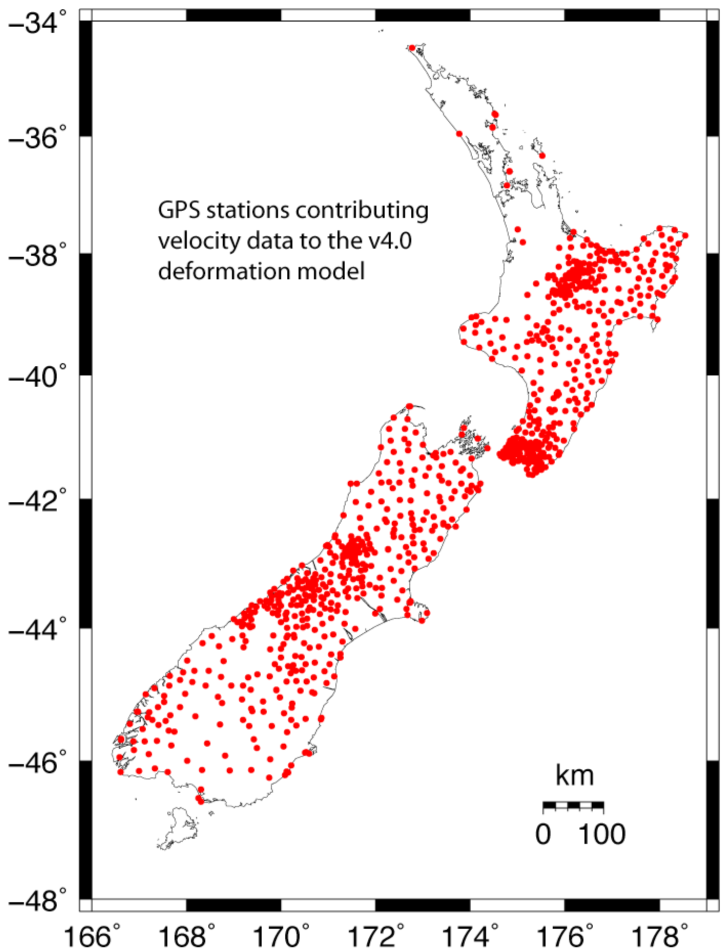

Figure A2 The 911 GPS sites contributing velocity data to the v4.0 deformation model.

The daily coordinate solutions have already been transformed to a particular ITRF realisation in the Bernese processing, as described in Section 2 of this report. VELFRAME nevertheless makes small reference frame adjustments, because: (1) it uses a slightly different set of reference stations; (2) it takes account of the variance/covariance matrix of the reference station positions and velocities (taken from the IGS SINEX files); and (3) we use a 7-parameter Helmert transformation to transform each daily solution. The transformation in Bernese uses an unweighted fit, with rejection of reference stations whose residuals exceed given criteria, and we have used only a 3-parameter translation at that stage of the processing.

We use GNS's in-house software, VELFRAME, to perform the solution, with the reference frame defined by a set of regional Australian, Pacific and Antarctic IGS stations (Table A2). We use these stations because they are available in both the IGS05 SINEX files and in our daily Bernese solutions. Within New Zealand, we process just the 29 zero- and 1st-order stations (excluding WELL) used in the original NZGD2000 analysis (Beavan, 1998). This is because the purpose of the analysis is to provide a uniformly-distributed set of IGS05 velocities that can be used to calculate transformations between the IGS05 and other reference frames. More details on the VELFRAME analysis are provided in Appendix B.

Our Bernese analysis included one IGS station (NOUM) that was not used to set the reference frame in VELFRAME (we do not consider MAC1 because its velocity is non-linear due to the 2004 earthquake). Our coordinates for NOUM agree with their IGS05 coordinates to better than 2.5 mm in all three components, and our velocities agree to better than 0.3 mm/yr, indicating that we have achieved a high level of consistency with the IGS05 reference frame, at least in this one case. This agreement compares very favourably with the various consistency checks described in Altamimi et al. (2007).

Table A2 Reference stations, coordinates and velocities

Site	DOMES No.	X, m	Y, m	Z, m	Vx, m/yr	Vy, m/yr	Vz, m/yr
			IGS05 (coordinates at 2000.0)				
ALIC	50137M001	-4052051.9586	4212836.1050	-2545105.6805	-0.0395	-0.0056	0.0541
CEDU	50138M001	-3753472.3711	3912741.0114	-3347960.7200	-0.0417	0.0007	0.0511
CHAT	50207M001	-4590670.9849	-275482.8716	-4404596.7082	-0.0257	0.0387	0.0244
DARW	50134M001	-4091358.9070	4684606.7121	-1408580.2927	-0.0350	-0.0146	0.0569
HOB2	50116M004	-3950071.4760	2522415.2101	-4311638.2398	-0.0403	0.0087	0.0408
KARR	50139M001	-2713832.3938	5303935.1039	-2269514.8516	-0.0445	0.0014	0.0540
MCM4	66001M003	-1311703.2146	310815.0718	-6213255.1140	0.0090	-0.0129	0.0000
PERT	50133M001	-2368687.1073	4881316.5395	-3341796.0076	-0.0468	0.0059	0.0529
THTI	92201M009	-5246415.3282	-3077260.2834	-1913842.3861	-0.0401	0.0532	0.0338
TIDB	50103M108	-4460996.2402	2682557.0825	-3674443.5584	-0.0371	0.0006	0.0455
TOW2	50140M001	-5054582.7913	3275504.4130	-2091539.5466	-0.0321	-0.0136	0.0522
YAR1/2	50107M004	-2389025.6733	5043316.8902	-3078530.5734	-0.0476	0.0094	0.0499

A4 Calculation of continuous horizontal deformation model

We use the 920 New Zealand site velocities from the ADJCOORD analysis as input to GNS's deformation mapping software (DEFMAP) in order to produce a continuous horizontal velocity field throughout the New Zealand mainland and near-offshore islands. The new data set of 920 independent velocities contains more than double the 391 independent velocities used by Beavan (1998) for the current LINZ deformation model (labelled v2.1 by GNS), and about 20% more than the 770 velocities used in the v3.0 velocity model (Beavan, 2008). The site distribution across the country is also much superior than in the original model (Figure A2), and the velocity estimates tend to have lower uncertainty due to the longer time interval, the improved quality of more recent data and the more uniform GPS data processing. The western boundary of the model is held fixed, which means that the velocity solution is in an Australia-fixed reference frame.

We have calculated the continuous velocity field using the same version of the software as was used for the v3.0 model (Beavan, 2008) but with an amended grid. The grid is shown in Figure A3. Information on the differences between the original and updated versions of the software can be found in Appendix D of the PONL-02 report (Beavan, 2008).

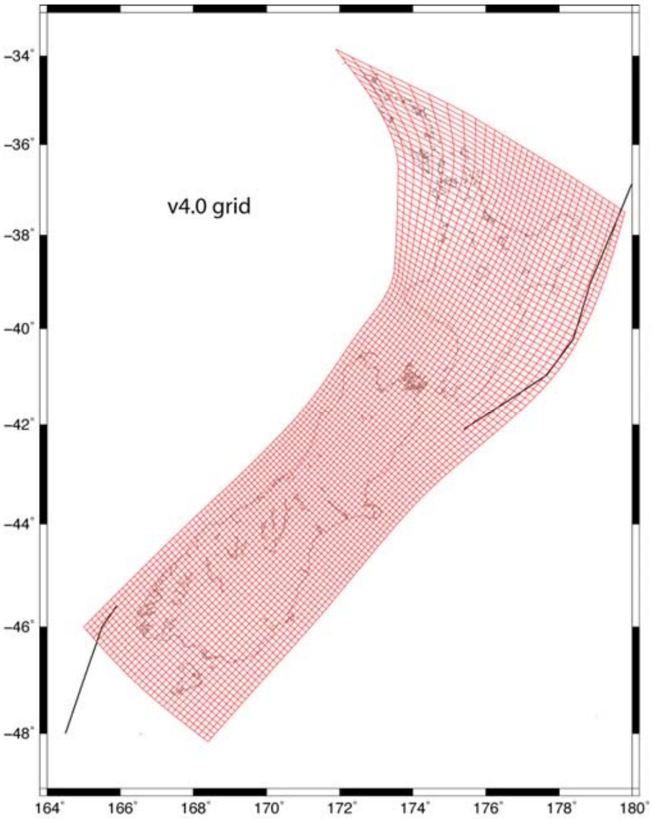

Figure A3 Grid used in v4.0 deformation model.

A5 Transformations between reference frames

The VELFRAME analysis provides velocities in the IGS05 reference frame and coordinates in the IGS05 reference frame at epoch 2000.0, for the set of 30 stations distributed through New Zealand. The DEFMAP analysis provides a continuous velocity model, in an Australia-fixed reference frame, that can be evaluated at the same 30 stations. We also have available the NZGD2000 coordinates and velocities of these 30 stations (Table A3). We use these coordinates and velocities to evaluate transformations between the reference frames.

For the velocity transformation between Australia-fixed and IGS05, we evaluate a 3-parameter Helmert transformation (3 rotations) between the v4.0 DEFMAP and the VELFRAME solution. The transformation is given in Table A4 in terms of an Euler rotation vector, as used in GNS's velocity modelling software. The RMS fit of the transformation is 0.6 mm/yr. In calculating the transformation, the VELFRAME vertical velocities are set to zero because DEFMAP does not include vertical velocities. We also evaluate the transformation from the v4.0 DEFMAP to the original NZGD2000 (ITRF96) velocity field (Table A4). The RMS fit is 1.5 mm/yr.

For the coordinate transformation between IGS05 and NZGD2000 at epoch 2000.0, we evaluate a 3-parameter Helmert transformation (3 translations), as there is no significant improvement of the fit when more parameters are added. The transformation parameters are given in Table A5.

In the PONL-02 report (Beavan, 2008) we used the NZGD2000 velocity field and equation (A1) below for transforming coordinates from the current epoch and current IGS reference frame to NZGD2000. In this equation, the values of **T**, *S* and **R** and their time derivatives are given in Table A5, t is the time in years since 2000.0, $(v_x, v_y, v_z)_{NZGD}$ is the velocity of the site expressed in Cartesian coordinates from the NZGD2000 deformation model, and *IGxx* denotes the current ITRF/IGS reference frame.

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{NZGD} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{IGxx} - t\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix}_{NZGD} + \left(\mathbf{T} + \dot{\mathbf{T}}t\right) + \left(S + \dot{S}t\right)\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{IGxx} + \left(\mathbf{R} + \dot{\mathbf{R}}t\right)\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{IGxx} \quad \text{(A1)}$$

Table A3 NZGD2000 coordinates and deformation model

	Coordinates at epoch 2000.0, NZGD2000			NZGD2000 velocities		
Name	**Lon**	**Lat**	**Ht, m**	**Ve, m/yr**	**Vn, m/yr**	**Vu, m/yr**
1004	167.738924057	-45.562114202	411.1960	-0.0229	0.0348	0
1017	169.197702098	-45.387644701	1680.8090	-0.0253	0.0328	0
1103	171.057344596	-44.400569527	397.1570	-0.0307	0.0332	0
1153	173.010278220	-42.687417778	405.5050	-0.0271	0.0333	0
1181	172.499523535	-41.729082571	1486.6460	-0.0054	0.0437	0
1215	175.652164178	-41.180141864	590.7910	-0.0292	0.0314	0
1231	175.488311848	-40.240198025	143.6090	-0.0125	0.0335	0
1259	174.228213410	-39.133999595	263.0410	0.0037	0.0414	0
1273	177.804852555	-38.575152214	323.4070	0.005	0.0199	0
1305	178.407103091	-37.824541932	360.4540	0.0141	0.0157	0
1314	176.466409162	-37.759466453	95.7270	0.0046	0.0364	0
1344	175.518603243	-36.333055071	438.0030	0.0064	0.0403	0
1361	173.769415957	-35.962107317	164.9700	0.0063	0.0417	0
1367	174.514359180	-35.617243980	174.4030	0.0057	0.0418	0
1394	172.771409170	-34.466585968	351.0500	0.0086	0.0431	0
1420	170.829658128	-42.953246399	919.3070	-0.0046	0.0415	0
1501	176.917245718	-39.478985214	119.2710	-0.0032	0.0239	0
2085	175.915026922	-38.616047237	760.2720	0.0025	0.0344	0
5508	172.743045187	-43.581503667	335.3550	-0.0318	0.0348	0
5509	168.253439043	-46.536929728	176.3430	-0.0263	0.0319	0
6731	169.003590817	-43.860817407	14.4120	-0.0063	0.0423	0
A31C	167.924065991	-44.673506600	9.5460	-0.0171	0.0413	0
A33D	175.000023214	-37.589384029	318.9120	0.0055	0.0407	0
A70X	172.672209514	-40.713000709	169.5390	-0.0007	0.0441	0
AUCK	174.834385556	-36.602844497	132.7110	0.0049	0.0404	0
B03W	166.609326421	-46.156391318	44.2640	-0.0201	0.0382	0
B28C	174.213808539	-41.749046004	254.5350	-0.024	0.0324	0
OUSD	170.510920749	-45.869501593	26.1970	-0.0311	0.0317	0
WGTN	174.805894058	-41.323457079	26.0730	-0.0246	0.0328	0

Table A4 Euler rotation parameters to convert Australia-fixed v4.0 horizontal deformation model to other reference frames

Reference frame	Latitude (deg)	Longitude (deg)	Rate (rad/10 Myr)
IGS05	-32.02	219.25	0.1085
NZGD2000 (IT96)	-31.09	220.03	0.1113

Table A5 Transformation parameters from IGS05 to NZGD2000 (NZ determination of ITRF96)

	Tx, **mm** $\dot{Tx}$, **mm/yr**	*Ty*, **mm** $\dot{Ty}$, **mm/yr**	*Tz*, **mm** $\dot{Tz}$, **mm/yr**	*S*, **ppb** $\dot{S}$, **ppb/yr**	*Rx*, **mas** $\dot{Rx}$, **mas/yr**	*Ry*, **mas** $\dot{Ry}$, **mas/yr**	*Rz*, **mas** $\dot{Rz}$, **mas/yr**	**RMS of fit**
PONL-02 report	-15.3±1.2 -1.58±0.3	-9.6±1.2 -1.19±0.3	-7.2±1.2 -0.91±0.3	0 0	0 0	0 0	0 0	6.1 mm 1.4 mm/yr
This report	-12.5±1.3 -0.5±0.3	-10.2±1.3 -0.99±0.3	-8.2±1.3 0.19±0.3	0 0	0 0	0 0	0 0	7.0 mm 1.3 mm/yr

For the current work, we have experimented with using either the NZGD2000 velocity field, or the v4.0 DEFMAP velocity field rotated into IGS05. In the latter case, equation (A2) below is needed. (This can be seen by examining equations (B2) and (B3) in Appendix B of the PONL-02 report.) In this equation, $(v_x, v_y, v_z)_{IGxx}$ is the velocity of the site from the current DEFMAP velocity model, rotated into the IGxx frame and expressed in Cartesian coordinates. We have found that the v4.0 DEFMAP velocity field and equation (A2) gives significantly better agreement with official NZGD2000 coordinates (from the LINZ GDB), compared to the NZGD2000 velocity field and equation (A1). This is probably because the NZGD2000 velocity field has significant errors, especially in some parts of the country (e.g., Raukumara, Figure B1) where limited data were available at the time of its construction.

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{NZGD} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{IGxx} - t\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix}_{IGxx} + \mathbf{T} + S\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{IGxx} + \mathbf{R}\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{IGxx} \quad \text{(A2)}$$

Equation (A2) and the parameters in the lower row of Table A5 are what we have used (since January 2011) in our work on the Canterbury earthquakes, when converting post-earthquake IGS05 coordinates to their post-earthquake NZGD2000 values.

APPENDIX B VELFRAME ANALYSIS

As each day's solution is added to the filter, VELFRAME updates the following parameters:

- 7-parameter transformation between daily solution and predicted position of the sites defining the reference frame
- position of each station
- velocity of each station

Each of these parameters is given an *a-priori* uncertainty, and an *a-posteriori* uncertainty is calculated after each day's processing using Bayesian statistics. The starting uncertainties for position and velocity are made large; the *a-posteriori* uncertainty on position decreases rapidly as data are added to the filter, while the *a-posteriori* velocity uncertainty takes some time to decrease. The GPS data are assumed to follow a white-noise process in this implementation of VELFRAME, so the final *a-posteriori* uncertainties are optimistic because of the neglect of the correlated noise in the GPS time series (e.g., Williams et al. (2004); see Beavan (2005) for New Zealand examples). (The uncertainties can be converted to realistic values using heuristic methods described by Williams (2003), but since our prime interest in this project is in comparing coordinate sets calculated in different reference frames, the values of the uncertainties are of limited importance.)

Where there are known offsets at individual stations (typically from antenna changes or earthquakes), the values of these offsets are provided to VELFRAME, and later data are corrected for the offsets when calculating station positions and velocities. This means that if the actual position of a station is to be calculated from the derived reference position and velocity, then the offsets must be added back at the appropriate times.

VELFRAME does not estimate the offsets; they have to be calculated elsewhere. Typically this is done by an examination of regionally-filtered daily position time series, with offsets detected and estimated either (1) by eye (using graphics software in which the level of the series before and after the offset can be shifted to give a visually-best fit), (2) by averaging short lengths of data either side of the offset, or (3) more rigorously, by using a maximum-likelihood procedure such as the "cats" maximum-likelihood software of Williams et al. (2004).

We make corrections for the 21 August 2003 Fiordland, 23 December 2004 Macquarie, 16 October 2007 Fiordland and 15 July 2009 Dusky Sound earthquakes, using the dislocation models discussed in Section A1.1 of Appendix A.

VELFRAME also includes a "time-constant" parameter that controls how rapidly the velocity of each station may vary as each new data set is added to the filter. This means that the filter is able to keep track of a station whose velocity is slowly changing, rather than insisting on a constant velocity. If a short time-constant is used, the final velocity estimate will be biased towards more recent data at the expense of older data. For the present processing we have kept the time constant long, 10,000 years, so that all data are weighted essentially equally (though still subject to the data variances).

After each day's coordinate solution has been added to the filter, a chi-squared-per-degree-of-freedom increment ($\Delta\chi^2_n$) is calculated. If this increment is much higher than 1, this is an indication that this day's solution may have problems; perhaps one or more stations should be excluded on this day, or perhaps the whole day should be excluded. We found only 3 days where $\Delta\chi^2_n$ exceeded 5 (and on all but 5 days it was less than 3), so we did not exclude any data from the VELFRAME analysis.

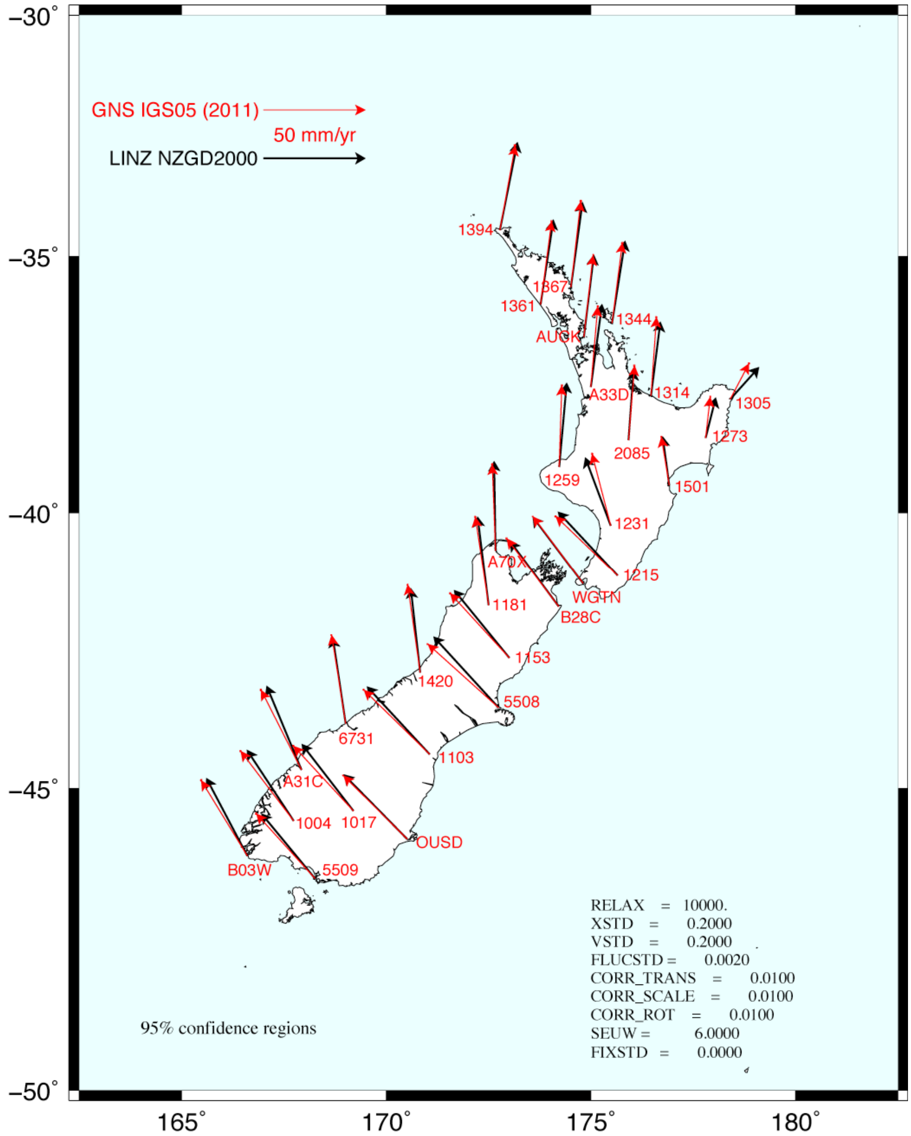

Figure B1 Estimated IGS05 velocity field (red arrows) at New Zealand zero-order and 1st-order sites. Also shown are the ITRF96 velocities used in the NZGD2000 velocity field (or LINZ deformation model) (grey).

The velocity solution in IGS05 is plotted in Figure B1, and listed in Table B1. The formal uncertainties are not given as they are unrealistically low, typically 1-1.5 mm in horizontal position, 3-5 mm in height, 0.2-0.3 mm/yr in horizontal velocity, and 0.4-0.8 mm/yr in vertical velocity. Stations A6RE, which has only a 2-year data span, and WELL, where the data series ended in 1997, are omitted.

In Figure B1, the parameters near the lower right of the plot have the following meanings. XSTD = 0.2 m and VSTD = 0.2 m/yr are the a priori position and velocity standard errors of a station before any data have been added to the filter. CORR_TRANS etc. are the a priori standard errors on the 7-parameter transformation of each day's solution to the reference frame realisation. They are each set to be equivalent to 0.01 m at the Earth's surface. SEUW is the factor by which the formal standard errors of the daily GPS solutions are multiplied before the data enter the filter. FLUCSTD = 0.002 m/yr is the standard error on velocity fluctuations, which describes how rapidly the estimated velocity may vary as new data are added. RELAX is the relaxation time in years for velocity correlations. FIXSTD is a standard error that may be added in quadrature to the formal standard errors of the daily GPS solutions, usually if a station has been tightly constrained in prior processing. We set FIXSTD to zero since station positions have been transformed to IGS05 but are not otherwise tightly constrained.

Table B1 Estimated coordinates and velocities in IGS05 reference frame

	Coordinates at epoch 2000.0, IGS05			Velocities, IGS05		
Name	**Lon, degrees**	**Lat, degrees**	**Ht, m**	**Ve, m/yr**	**Vn, m/yr**	**Vu, m/yr**
1004	167.738923822	-45.562114235	411.1916	-0.0260	0.0342	0.0001
1017	169.197701845	-45.387644739	1680.7911	-0.0294	0.0319	-0.0026
1103	171.057344425	-44.400569598	397.1331	-0.0322	0.0315	-0.0018
1153	173.010278063	-42.687417828	405.4869	-0.0290	0.0317	-0.0008
1181	172.499523404	-41.729082574	1486.6349	-0.0064	0.0436	-0.0018
1215	175.652164016	-41.180141898	590.7707	-0.0302	0.0292	-0.0050
1231	175.488311887	-40.240197993	143.5794	-0.0091	0.0352	-0.0018
1259	174.228213282	-39.133999615	263.0223	0.0013	0.0400	0.0001
1273	177.804852365	-38.575152190	323.3830	0.0022	0.0202	-0.0013
1305	178.407102856	-37.824541866	360.4289	0.0091	0.0174	0.0001
1314	176.466409065	-37.759466387	95.7032	0.0027	0.0385	0.0000
1344	175.518603132	-36.333055088	437.9822	0.0050	0.0393	-0.0015
1361	173.769415908	-35.962107321	164.9470	0.0054	0.0406	-0.0014
1367	174.514359096	-35.617243957	174.4027	0.0048	0.0421	0.0073
1394	172.771409100	-34.466585986	351.0212	0.0075	0.0414	-0.0017
1420	170.829657936	-42.953246347	919.2937	-0.0061	0.0431	0.0001
1501	176.917245612	-39.478985179	119.2458	-0.0038	0.0237	-0.0005
2085	175.915026867	-38.616047173	760.2399	0.0030	0.0364	-0.0027
5508	172.743044983	-43.581503755	335.3400	-0.0346	0.0312	-0.0010
5509	168.253438860	-46.536929726	176.3313	-0.0287	0.0316	-0.0003
6731	169.003590687	-43.860817396	14.4064	-0.0069	0.0433	0.0003
A31C	167.924065748	-44.673506678	9.5482	-0.0198	0.0391	-0.0008
A33D	175.000023113	-37.589384038	318.8936	0.0034	0.0395	-0.0005
A70X	172.672209387	-40.713000772	169.5383	-0.0016	0.0424	-0.0007
AUCK	174.834385449	-36.602844504	132.7090	0.0045	0.0401	-0.0010
B03W	166.609326201	-46.156391361	44.2581	-0.0226	0.0370	-0.0031
B28C	174.213808418	-41.749045962	254.5023	-0.0254	0.0335	-0.0030
OUSD	170.510920654	-45.869501633	26.1640	-0.0312	0.0312	-0.0007
WGTN	174.805893953	-41.323457092	26.0611	-0.0245	0.0330	-0.0021

APPENDIX C USE OF DEFORMATION MODEL SOFTWARE

The velocity model is contained in the file solution.gns. The version number (v4.0), date (20-jan-2012), and standard error of unit weight (1.56) are included in the first line of the file.

The fortran code to generate point velocity estimates from solution.gns is in file gns_velocity.f.

gns_velocity expects a data file named lat_long.dat that contains as its first line the number of points to follow. Succeeding lines contain an index number, latitude and longitude for each point. The latitude (positive north) and longitude (positive east) are entered in decimal degrees. The point must lie within the boundaries of the grid displayed in Figure A3. An example lat_long.dat file is:

```
4
1  -42.355   176.398
2  -43.65657 174.5676
3  -41.99827344  173.39387489
4  -44.4     171.45
```

gns_velocity issues two prompts. The first states that there are no variances and covariances and asks if you wish to continue; you need to answer “Y”. The second asks for the latitude, longitude and rate for the pole of rotation of the reference frame. Since the velocity solution stored in solution.gns is with respect to an Australia-fixed reference frame, you should reply "0 0 0" if you wish for velocity results with respect to Australia. If you wish for results with respect to another reference frame then you should enter the latitude, longitude and rate of rotation of that frame with respect to Australia. The values should be entered in decimal degrees for the coordinates and in radians per 10 million years for the rate. gns_velocity outputs its results to a file called velocity.out, with the velocities and standard errors in unconventional units of Earth radius/10 Myr. To convert these to mm/yr, you need to multiply by 637.1.

A run of gns_velocity producing velocities relative to Australia would look like:

```
% gns_velocity
   No variances and covariances
Do you want to continue (Y/N)?
Y
 Enter the latitude and longitude (in degrees) of the Euler
  pole for the frame of reference and the rotation rate to
   be removed
0 0 0
%
```

To generate velocity results in IGS05, the run would look like:

```
% gns_velocity
   No variances and covariances
Do you want to continue (Y/N)?
Y
 Enter the latitude and longitude (in degrees) of the Euler
  pole for the frame of reference and the rotation rate to
   be removed
-32.02  219.25  0.1085
%
```

No standard error or correlation estimates are produced by gns_velocity because there is no uncertainty information in the v4.0 solution.gns file. The standard error of unit weight in the header line is therefore not used.

A spline-fitting and inversion procedure is necessary to locate the requested point within the curvilinear grid and interpolate the gridded velocity to that point. We expect that LINZ will wish to speed up the procedure by using the GNS model to generate the velocity solution on a fine latitude-longitude or NZTM grid that may then be interpolated rapidly, and/or by reformatting the ascii data file in binary. We expect that LINZ may also wish to make changes to gns_velocity.f. In order to maintain compatibility between GNS and LINZ software, GNS will supply updates to the velocity model in the format of solution.gns, unless it is mutually agreed by GNS and LINZ that a format change should be made.

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