THE DARFIELD (CANTERBURY) EARTHQUAKE OF SEPTEMBER 2010: PRELIMINARY SEISMOLOGICAL REPORT

Ken Gledhill[1], John Ristau[1], Martin Reyners[1], Bill Fry[1], and Caroline Holden[1]

SUMMARY

The Darfield moment magnitude (M_w) 7.1 earthquake of September 2010 is the first heavily damaging earthquake to strike New Zealand since the surface wave magnitude (M_S) 7.8 Hawkes Bay earthquake in 1931. Although the earthquake has a clear strike-slip surface expression characterised by the Greendale Fault, seismological evidence suggests it is a complex event beginning as a reverse faulting earthquake. Evidence for complexity of the mainshock includes a well constrained epicentre north of the surface fault trace, high near-source vertical accelerations, first-motion and regional moment tensor focal mechanisms which differ from teleseismic solutions, and a complex aftershock pattern. The earthquake and aftershock sequence were very well recorded by the GeoNet sensor networks in the region, and provide an exceptional dataset for understanding the earthquake rupture process and reducing damage from future earthquakes. This was the most significant test of GeoNet since its inception in 2001, and the first such New Zealand event in the "internet age". GeoNet data proved important for the response and the interaction with emergency management, media and the public. The GeoNet website sustained continued heavy load over the weeks and months following the earthquake but continued to deliver timely information because of significant improvements carried out as the aftershock sequence continued.

INTRODUCTION

The Darfield moment magnitude (M_w) 7.1 earthquake is the first high-impact geological event to affect the New Zealand community in the "internet age", and the first such event in this country since the establishment of GeoNet in 2001. Not since the surface wave magnitude (M_S) 7.8 Hawkes Bay earthquake of 1931 [1], almost 80 years ago, has a New Zealand city experienced this level of earthquake shaking intensity. There was no loss of life in the earthquake and only two serious injuries. In contrast recent international earthquakes of a similar size (e.g. Haiti, January 2010, [2]) have caused significant loss of life.

The Darfield earthquake was centred under the Canterbury Plains where no active faults had previously been mapped and no large historical earthquakes are known to have occurred. However, further west in the foothills of the Southern Alps there are a number of mapped active faults and several M > 6-7 earthquakes have occurred in the past 150 years. These include 1888 North Canterbury, M_w 7.1 [3]; 1929 Arthur's Pass, M_w 7.0 [4]; 1994 Arthur's Pass, M_w 6.7 [5]; and 1995 Cass, M_w 6.2 [6].

We already know a considerable amount about this earthquake because of the data available from the GeoNet [7] sensor networks, the surface faulting [8], and modern analysis techniques that have quickly established the gross nature of the earthquake source using a large amount of New Zealand-based and international data [9]. Two of the key aspects of the earthquake are the obvious complexity of the source, and the degree of liquefaction damage [10].

In this paper we will present the preliminary seismological information on the Darfield earthquake and introduce the high-quality data now available to improve our understanding of earthquake source processes and the resulting damage. The usefulness of the freely available GeoNet data will be highlighted and its contribution to the effectiveness of the response underlined.

THE EARTHQUAKE

The key seismological features of the Darfield earthquake are summarized in Table 1 and Figure 1. The M_w 7.1 earthquake occurred at 4:35 am on Saturday 4 September New Zealand Standard Time at a depth of 10.8 km, approximately 37 km west of the centre of Christchurch, New Zealand's second largest city. The epicentre and depth are very well determined because of the large number of nearby GeoNet sensor network sites. The earthquake caused significant damage in Christchurch and the surrounding region but no loss of life. There were about 100 people injured, two of them seriously. A key feature of the earthquake was the extensive liquefaction in various parts of the region, which caused damage to even modern buildings. The style and severity of the building damage caused by the earthquake are detailed elsewhere in this volume [10]. The earthquake was felt throughout the entire South Island and a large part of the North Island, with the maximum felt intensity estimated to be MM 9, and over 7,000 felt reports were submitted to the GeoNet website (Figure 2). Measured accelerations near source topped 1 g with several reading well over 0.5 g. A feature of the near-source strong-motion recordings is the high level of vertical acceleration.

[1] *GNS Science, PO Box 30368, Lower Hutt, NZ.*

A right-lateral strike-slip surface fault has been identified about 4 km south of the epicentre. It has been named the Greendale Fault and has a cumulative length of 29 km striking east-west with maximum displacements of up to 5 m horizontally and 1.5 m vertically (Figure 1). Details of the surface fault trace are reported elsewhere in this volume [8].

Several estimates of the focal mechanism of the Darfield earthquake are available. The first motion and the regional moment tensor focal mechanisms are in very good agreement, but quite different from the teleseismic moment tensor solutions (Figure 3). The teleseismic moment tensor solutions [11, 12] indicate a strike-slip source mechanism in agreement with the Greendale Fault sense of slip; whereas, the regional moment tensor and first motion source mechanisms show a large reverse faulting component. This difference in focal mechanisms does not imply that either estimate is wrong, but rather highlights the difference in the techniques. The teleseismic methods provide a far-field view of the overall source whereas the other two techniques will be more sensitive to the beginning or first phase of the rupture process.

Source properties of large earthquakes have historically been analyzed by looking at waveforms recorded at regional or greater distances. The minimum-sized feature that a wave is sensitive to is dependent on frequency. High-frequency waves are sensitive to small-scale features whereas low-frequency waves are sensitive to larger features. When a distant earthquake is recorded, the signal is dominated by low-frequency content, as most of the source-generated high-frequency signal is attenuated during the wave's propagation. Furthermore, as the wave-trains from an earthquake propagate, they are dispersed, creating an elongation of the recorded coda. In a situation in which multiple ruptures contribute to the total energy release, dispersion can superimpose their individual signals, even if the two mechanisms are spatially or temporally separated. This is likely to be the case with the Darfield earthquake, and this can only be resolved using the near-source data recorded by GeoNet.

The Darfield earthquake has been followed by a reasonably energetic aftershock sequence (Figure 4). To date (end of October 2010) there have been 12 aftershocks of local magnitude (M_L) 5 or greater (Table 2) and 132 between M_L 4 and 5, but because of the shallow depth and proximity to the city many more have been felt by residents in the region, some of which are as small as M_L 2.5. Several of the events in the magnitude 5 range have caused additional damage and concern, particularly those within or very near Christchurch city.

Table 1. Key seismological features of the Darfield earthquake.

Origin Time	September 3, 2010 at 16:35 UT (September 4, 2010 at 04:35 NZST)
Epicentre	-43.55, 172.17
Depth	10.8 km
Magnitude	7.1 M_W
Maximum Intensity	MM9
Location	9 km south-east of Darfield 37 km west of Christchurch

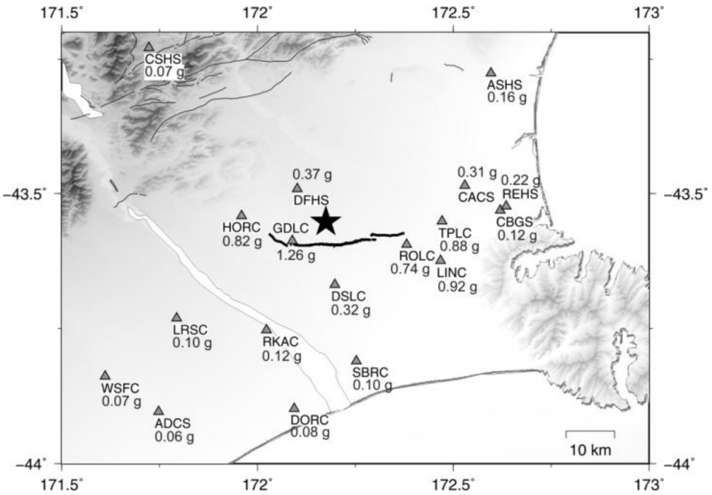

Figure 1: ***Map of central Canterbury showing the Greendale Fault, the epicentre of the Darfield earthquake (black star) and the vertical PGAs at selected strong motion sites. Not all sites are shown for clarity. Active faults are from the GNS Science active faults database and the Greendale fault trace was provided by [8].***

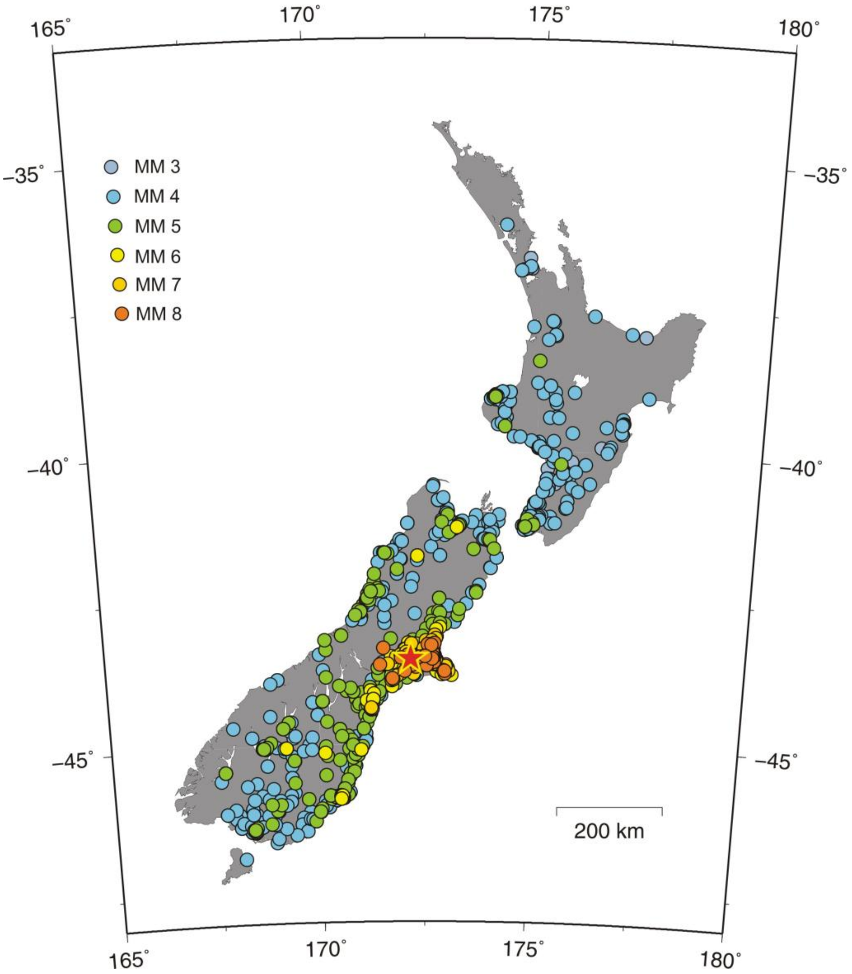

Figure 2: ***Map showing the extent of the felt reports received to date by the GeoNet website. Epicentre is denoted by the red star. MM 9 and above values are assigned by engineers and are not derived automatically; therefore, no MM 9 values appear on this map.***

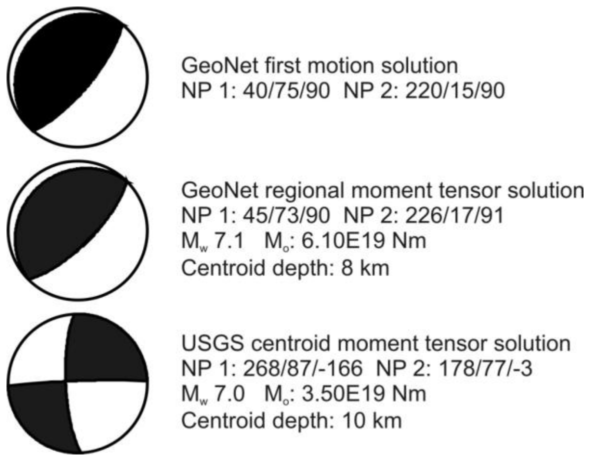

Figure 3: ***The GeoNet first motion solution (top), GeoNet regional moment tensor (middle), and USGS centroid moment tensor (bottom) focal mechanisms of the Darfield earthquake with some of the key parameters noted: the strike/dip/rake of both nodal planes (NP), and for the moment tensor solutions M_w, seismic moment (M_o), and centroid depth.***

Table 2. Preliminary parameters of the larger aftershocks.

Origin Time (NZST)	Epicentre	Depth (km)	Magnitude (M_L)
2010/09/04 04:56	-43.67, 172.18	10.1	5.6
2010/09/04 07:56	-43.60, 172.40	5.0	5.1
2010/09/04 11:12	-43.55, 172.16	9.0	5.3
2010/09/04 16:55	-43.57, 171.97	5.0	5.4
2010/09/05 05:20	-43.63, 171.14	5.0	5.0
2010/09/06 23:24	-43.60, 172.41	12.0	5.1
2010/09/06 23:40	-43.60, 171.85	5.0	5.4
2010/09/07 03:24	-43.65, 172.24	11.3	5.3
2010/09/08 07:49	-43.59, 172.72	6.6	5.1
2010/10/04 22:21	-43.57, 172.39	5.0	5.2
2010/10/14 02:02	-43.59, 172.41	10.9	5.0
2010/10/19 11:32	-43.63, 172.56	8.9	5.0

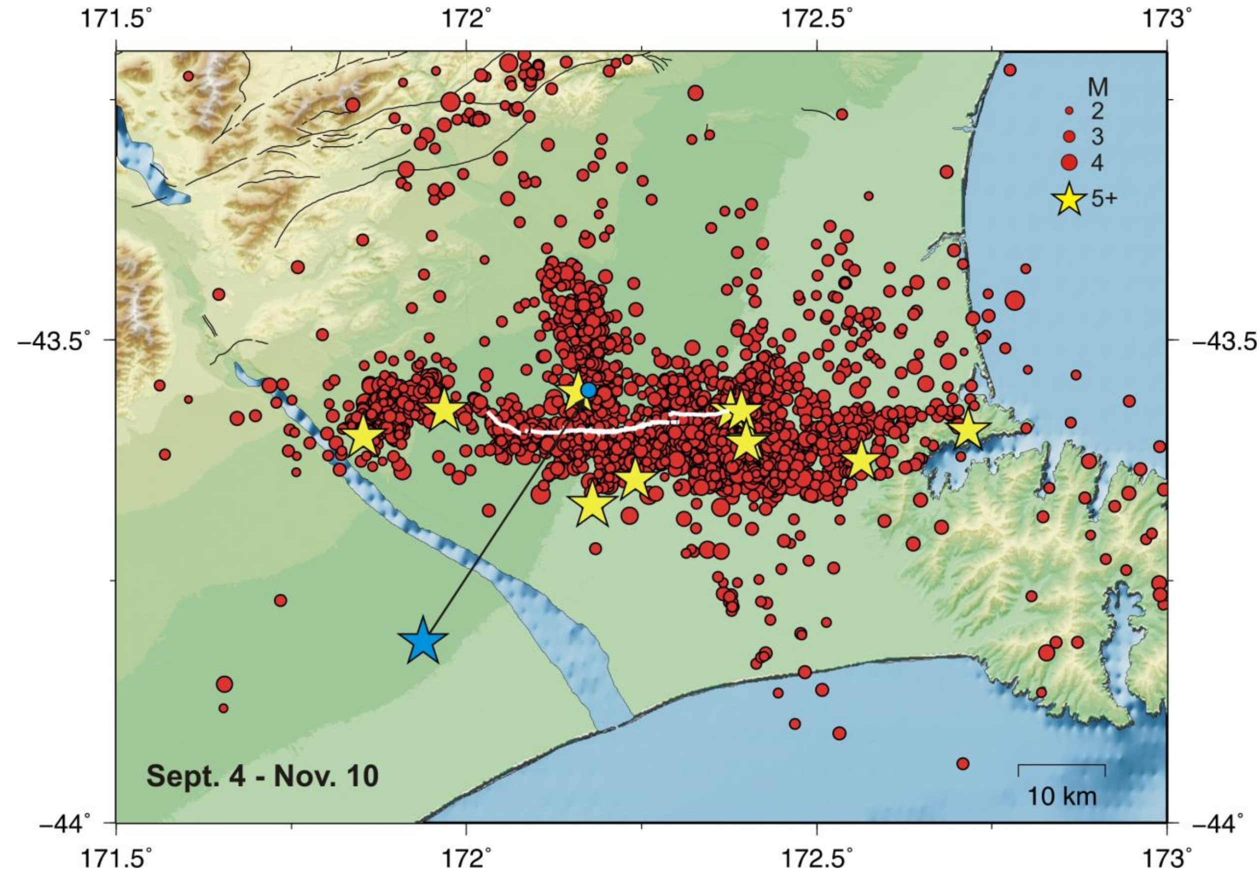

Figure 4: ***Map of the preliminary aftershock locations. Note the "finger" of aftershocks trending north from the epicentre and the cluster of aftershocks at the western end of the fault trace. Yellow stars are $M_L \geq 5.0$ aftershocks and the blue star points to the epicentre. Thick white line is the Greendale fault trace ([8]) and the active faults are from the GNS Science active faults database.***

GEONET DATA AND INFORMATION

The Darfield earthquake was very well recorded by both the broadband and strong-motion national-scale GeoNet networks [13] and the Canterbury regional strong-motion network (CanNet). All operational GeoNet real-time sites and a large number of the triggered strong-motion sites recorded the earthquake (a total of 295 sites) and provided waveform data to the GeoNet data centre. There is also a set of building response records from the building array installed in the physics building at the University of Canterbury.

Some of the best near-field ground-shaking measurements of the Darfield earthquake were recorded by the sensors of the CanNet network, a set of low-cost accelerographs installed throughout the Canterbury Plains and within Christchurch city. CanNet was installed as a part of GeoNet to capture the impacts of a rupture of the Alpine Fault to the west, but instead is playing a major role in unscrambling the complex nature of this significant earthquake. In total, GeoNet obtained 38 strong ground motion recordings within 50 km of the epicentre. This is an exceptional dataset which seismologists are currently using to better define the complex history of the rupture using inversion methods as well as recently developed source-tracking methods. More information and analysis of the strong ground motion data are contained in a companion paper [10].

The data from GeoNet are freely available and have been widely used by the response agencies, the engineering companies advising the Earthquake Commission, and the general community. Several third-party websites have been established which use GeoNet data feeds to present the information in novel ways, demonstrating the power of open data, e.g. the University of Canterbury combining GeoNet aftershock locations with Google Earth to create an animation of the aftershocks over time. During September over 580 gigabytes of waveform data from GeoNet were provided to New Zealand and international research institutions.

Despite the damage caused by the earthquake and the fact that power was lost in large parts of Christchurch city, data were successfully collected in near-real-time from most of the GeoNet sensor networks in the region. At one stage it was reported in the media that up to 50% of the cell phone sites within the region were unavailable, and while this may have slowed some of the strong-motion records which use cell phone technology for data transfer, there was no overall data loss. Communications with one site, which relays data through the University of Canterbury, and the strong-motion building array at the university, were lost, but the data from these sites were retrieved successfully once power was restored.

THE GEONET RESPONSE

The GeoNet sensors in the epicentral region recorded the large velocities and high accelerations almost as soon as the rupture began. This waveform data arrived at the GeoNet data centres within seconds and automated processes began the analysis. Within a couple of minutes the systems had made the first estimate of earthquake location and began to notify a "serious page" to the GeoNet duty team and provided a map of instrumental shaking intensities on the GeoNet website (Figure 5). Shaking recorded by the seismographs are converted into expected intensities to get the shaking intensity map; whereas, the felt report map shows the intensity levels as actually reported by people. The duty seismologist logged onto the GeoNet computer at Avalon (Lower Hutt) and began the process of refining the automatic location. The instrumental shaking map clearly showed that the worst effects were near Christchurch and before the epicentre and size of the earthquake had been confirmed we had notified the Ministry of Civil Defence and Emergency Management (MCDEM) that a large, potentially destructive earthquake had occurred near New Zealand's second largest city.

There is a universal problem determining the size of a large earthquake from nearby stations. Distant recordings (which sum the lower frequency energy) are required to give a reliable magnitude so our original magnitude estimate, based on preliminary international information was high. This was quickly revised to the currently accepted value of M_w 7.1, in good agreement with current international estimates.

GeoNet, which is largely funded by the Earthquake Commission to monitor New Zealand's geological hazards, has both rapid response and research data collection functions. Because of the capability provided by GeoNet, GNS Science, which has designed, built and operates the facility has a memorandum of understanding with MCDEM with defines performance standards for all geological perils. This event was the first full-scale test of GeoNet and the related response functions since the inception of the facility in 2001, although we have responded to four other large earthquakes (the largest being the M_w 7.6 Dusky Sound earthquake of July 2009 [14]) and three tsunami events in recent years. Under the Memorandum of Understanding (MoU) GNS Science is the scientific adviser to MCDEM on the major geological perils, and we provide a liaison scientist to contribute scientific input for the national response – an effective example of science to practice.

To better record the aftershock sequence, GNS Science installed an additional 10 portable seismographs and three accelerographs within the aftershock zone, and 10 accelerographs within Christchurch city. Several other institutions have installed portable seismographs to assist regional studies.

The Darfield earthquake and its aftershocks caused a great deal of traffic to the GeoNet website [7]. In the first five days after the quake, the website served more traffic than for the entire 2009 year. For the month of September the website served over 564 million hits, equating to more than 1 terabyte of web traffic. Over 56,000 felt reports were also received during September, adding to the load on the web server infrastructure. This huge increase in web traffic over a very short period of time presented some challenges and occasionally pushed the servers to their limits. Due to the flexible design of the website hosting, we were able to expand the capacity by installing additional web servers as interest in the aftershocks grew. Recent larger aftershocks have pushed the web traffic to new highs of over 11,000 requests per second.

A feature of the Darfield earthquake has been the extensive use of social media for the sharing of information. GeoNet earthquake reports are now sent to both Twitter [15] (currently with ~2300 "followers" but also a large number of re-tweets and third party providers) and Facebook [16] (currently with ~4,000 "friends"), and after each larger aftershock Twitter is swamped with messages reporting what people have felt (hashtag #eqnz), and demanding that GeoNet hurry up and post the location and magnitude. This starts within seconds of the aftershock occurring and highlights the thirst for timely information.

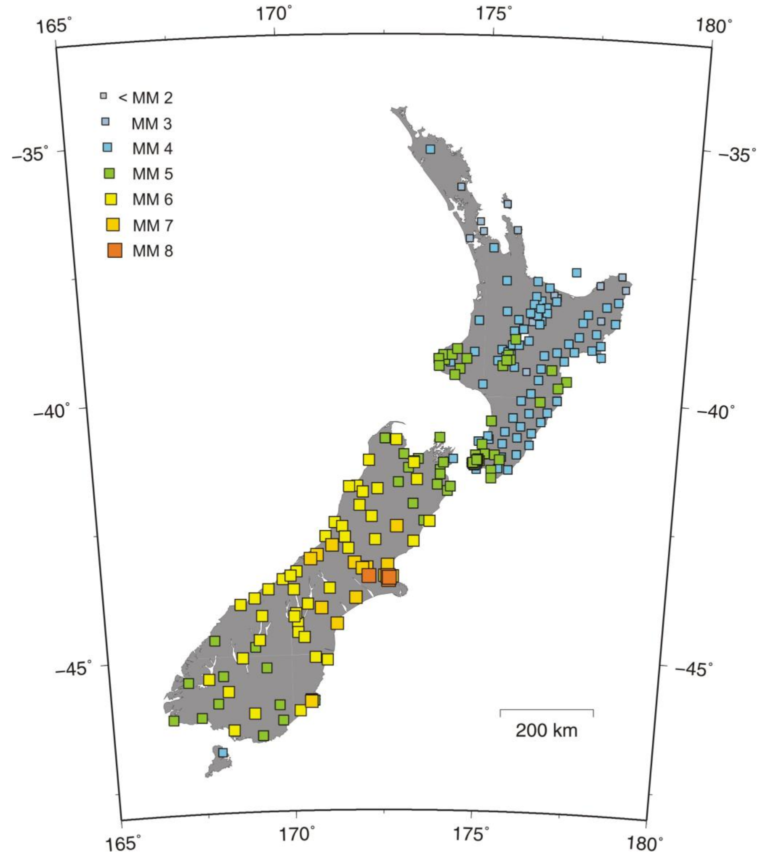

Figure 5: ***Instrumental shaking map as displayed on the GeoNet website front page. Shaking as recorded by the seismographs is converted into expected intensity levels.***

DISCUSSION

There are several lines of evidence that suggest that this earthquake is not a simple strike-slip event. Although the hypocentre of the Darfield earthquake is very well determined (within at most ±0.5 km), the epicentre is a considerable distance from the surface trace of the Greendale Fault. This cannot be explained by location uncertainty or by dip on the fault which is likely to be near vertical. The second important piece of evidence comes from the various estimates of the focal mechanism of the earthquake. There is a clear difference between the teleseismic moment tensor methods, which indicate a strike-slip source mechanism in agreement with the Greendale Fault trace orientation, and the regional moment tensor and first-motion source mechanisms (Figure 3), which are in close agreement and show reverse faulting. The teleseismic moment tensor methods provide an average over the whole event, whereas the other two methods are modelling the nature of the first part of the rupture.

The teleseismic broadband energy solution [17] indicates a complex event with at least two sub-events. Although the first sub-event has less moment than the later sub-event, it appears to have a much greater amount of radiated energy.

The aftershock distribution (Figure 4) shows a SSE-oriented "finger" of aftershocks off the main alignment towards Darfield, particularly if only the early aftershocks are considered. The aftershock focal mechanisms show a variety of faulting styles providing additional evidence for the complex nature of the rupture process. There is a cluster of aftershocks at the western end of the fault trace where the focal mechanisms for the larger events are predominantly reverse faulting. Additionally, near-source strong-motion stations show unusually high vertical accelerations which require an initial thrust component to the event. Preliminary geodetic results [9] show a complex source with several thrust faults in addition the strike-slip Greendale fault. This multiple-fault geodetic model could help explain the aftershock distribution.

The above observations suggest that this earthquake began as a reverse faulting (thrust) event at the determined hypocentre and continued in a strike-slip sense along the Greendale Fault to accommodate the displacement and the regional stress. A full multi-disciplinary study is required to quantify the styles and the sequence of the rupture, but no other hypothesis explains the seismological observations. The USGS calculated an energy magnitude (M_e) 7.4 for the Darfield earthquake [17]. Compared with M_w 7.1 this implies a high apparent stress for the event and a large amount of seismic energy. The large amount of seismic energy is presumably partially responsible for the extensive liquefaction observed; however, a great deal of work on this aspect still needs to be carried out. In a New Zealand and international context this is not a particularly unusual scenario, with the 1994 Arthur's Pass [5] and 1995 Cass [6] earthquakes in the Canterbury region both likely to have been complex events. International examples include the 1992 Lander's earthquake in California [18], and the 2010 Haiti earthquake which exhibited complex rupture processes similar to Darfield [2]. The difference in the case of the Darfield earthquake is that the mainshock was very well recorded by many nearby instruments which will allow, over time the full characterisation of not only what happened, but provide an explanation of the sequence and dynamics of the multiple ruptures.

CONCLUSIONS

The seismological evidence suggests the Darfield earthquake of September 2010 is a complex event involving the rupture of multiple fault structures. It began as a reverse faulting rupture at the hypocentral location but continued to rupture the surface as a right-lateral strike-slip fault. Considerable research is still required to fully characterise the Darfield earthquake and its impacts. From a seismological point of view this will involve the integration of various source-modelling techniques to form a preferred source model and analysis of the aftershocks to put the earthquake in a tectonic context. A full multi-disciplinary study involving geodesy (GPS and satellite radar imagery), seismology (strong-motion and aftershock studies) and geology is underway to constrain the rupture process. This is important both in a regional tectonic context, but also to help in the understanding of the patterns of damage and liquefaction.

The Darfield earthquake was the first earthquake to impact New Zealand in the "internet age" (including the even newer social media technologies), and this was important for how information about the earthquake was delivered to responding agencies and the wider community. The GeoNet website played a very important role in this process, but the open data access policy allowed many third party websites new and exciting ways to play their part. It is hard to imagine how the thirst for information caused by this earthquake could have been managed without the existence of GeoNet. The whole of GeoNet performed as designed, from the sensor networks, through the data communications system to data handling, analysis and determination.

ACKNOWLEDGMENTS

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