

Post-earthquake seismic reflection survey, Christchurch, New Zealand

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Summary

Approximately 42 line-km of high-fold reflection seismic data were recorded in and around the city of Christchurch, New Zealand, following a devastating Mw 6.3 earthquake on February 22, 2011. The goal of the seismic program was to map previously unknown faults in and around the city for hazard assessment and to assist in the post-earthquake recovery effort.

Seismic data were collected along six 2D lines, two of which were within the Christchurch metropolitan area and four were in rural areas west of the city. Recording conditions were challenging within the city, but good quality images were obtained along all of the seismic lines, with events interpretable to a depth of approximately 1.5 km. Numerous faults were imaged along the lines and these were interpreted in two groups – older faults that showed clear offsets in deep (> 1 km) reflections and younger faults that showed displacement in shallow reflections. Some faults in the latter group were interpreted to be directly associated with hypocentres of the earthquake and aftershocks.

Introduction

On September 4, 2010, an earthquake struck the Christchurch region in New Zealand. The Mw 7.1 quake was centred about 40 km west of the city of Christchurch and caused significant damage but no loss of life. A key manifestation of the earthquake was a fault that ruptured to the ground surface with a maximum right lateral displacement of 4.5 m and a vertical displacement of 1.5 m, upthrown to the south (Quigley et al., 2010). The fault trace at the surface was ~28 km long and was oriented approximately east-west, towards the city. On February 22, 2011, a Mw 6.3 aftershock struck with a shallow hypocentre very close to the city. This earthquake resulted in the loss of 182 lives and devastating damage (\$23B) to the city infrastructure, buildings and homes. Since September, 2010, the region has experienced over 10,000 aftershocks, with 2662 of these being greater than 3M.

Soon after the February 22, 2011 earthquake struck the University of Calgary's 600-channel Aries seismic recording system and Envirovibe were air-freighted to New Zealand to undertake urgently-required seismic profiling in and around Christchurch to assist in identifying shallow fault systems for aftershock risk assessment and natural hazard identification. This paper describes the program,

which illustrates how exploration seismic technology can be applied in the case of a societal need.

Background

New Zealand lies in a tectonically active area and straddles the boundary between the Australian and Pacific plates. Figure 1 shows a tectonic map of the south island of New Zealand, with the Christchurch region highlighted in the green circle. The major tectonic feature in the South Island is the Alpine Fault, with numerous splays to the north. The known fault network in the Canterbury Plains region is shown in Figure 2, with most of the faults mapped to the west and north of Christchurch. The epicentres of historical earthquakes with Mw > 6 are also shown. Those greater than Mw 7 are located close to the Alpine Fault and only 2 earthquakes were known to have occurred near Christchurch since event data had been recorded.

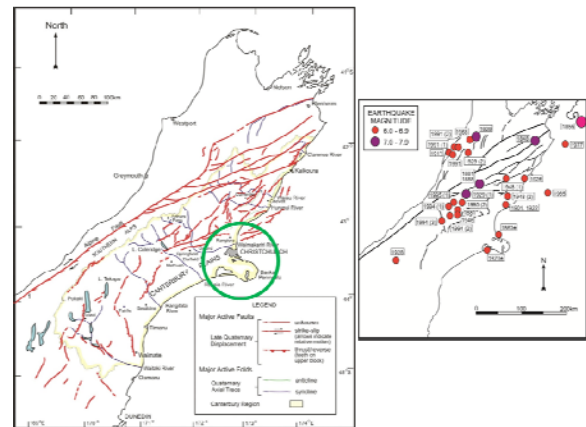


Figure 1. Tectonic and seismicity map of the South Island, NZ. Christchurch region is in the green circle (after Pettinga, 1986).

Method

High fold 2D seismic lines were recorded in and around the city using the Envirovibe seismic source and 600-channel recording system. The layout of the seismic lines is shown in Figure 2. Line 1 was recorded along the beach immediately to the east of the city and Line 2 was recorded along one of the main streets near the city centre. This region of the city was closed to public access because of severe infrastructure damage and proximity to unstable

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buildings. Lines 3 and 5 through 7 were recorded west of the city to investigate ‘step-overs’ in the pattern of shallow epicentres.

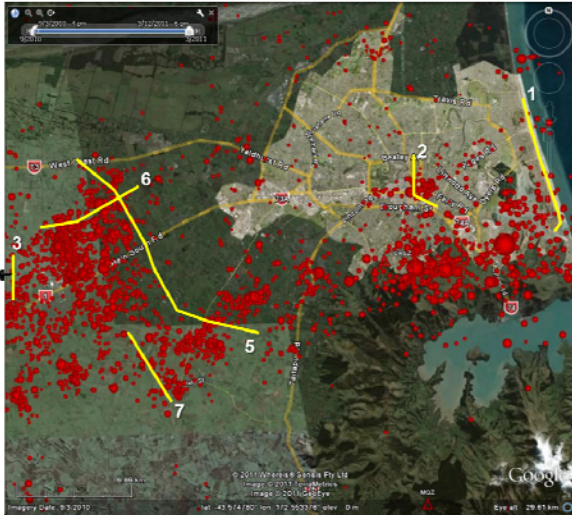


Figure 2. Layout of 2D seismic lines. Red dots show the epicentres of aftershocks through to June, 2011. Map data © 2011 Europa Technologies and © 2011 Google and © 2011 Whereis® Sensis Pty Ltd. Imagery © 2011 NASA.

Recording parameters of the seismic survey are summarised in Table 1 following tests carried out on Lines 1 through 3.

Parameter	Value
Receiver interval	10 m on all lines
Receiver type	Single SM24 10 Hz vertical component geophones
Source interval	Nominally 20 m but 10 m on some lines
Source sweep	4 x 10 Hz - 120 Hz over 20 s (Line 1) 8 x 10 Hz - 120 Hz over 10 s (Lines 2 – 7)
Listen time	4 s
Source type	9000 kg Envirovibe
Sample interval	1 ms
Nominal spread geometry	2000 m - 10 m - VP - 10 m - 2000 m

Table 1. Seismic acquisition parameters

Results

Line 1 was the first line recorded during the survey and it is located along the Pacific Ocean beach on the east side of the city (Figure 6). It was 8 km in length. Recording this line had some challenges with soft sand, wave noise and tides.

The interpreted seismic line from Line 1 is shown in Figure 3. The image is dominated by an event that dips from south to north. This is interpreted to be the surface of volcanic rocks from the Lyttelton volcano, the centre of which outcrops southeast of Christchurch. The seismic section has been converted to depth using a velocity function of 2000 m/s at sea-level to 2800 m/s at 1 km depth.

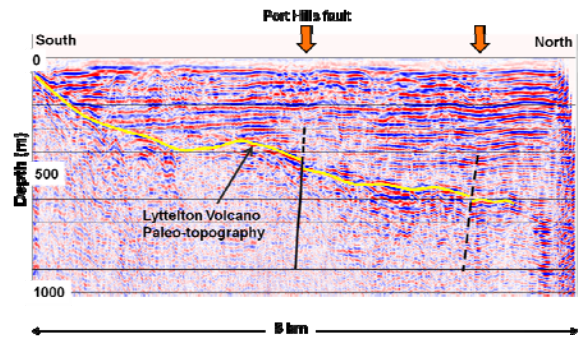


Figure 3. Interpreted seismic Line 1. The Port Hills Fault contains the hypocentre of the Mw 6.3 aftershock.

Because of the limited power of the Envirovibe source, little seismic energy was able to penetrate the volcanic sequence and no reflections could be interpreted below the top volcanic reflector. Discontinuous, near-horizontal reflections from young, unconsolidated sediments lap out against the volcanic interface (Figure 3). These sediments are made up primarily of alluvial to shallow marine sands and gravels deposited from large rivers that have catchments in the Southern Alps to the west.

Two faults are interpreted in this section, identified because of significant offsets in the Lyttelton volcanic events. These faults are considered to post-date the volcanics but pre-date most of the younger sediments as no obvious offsets in reflection patterns can be observed in the sub-horizontal reflections. The fault near the centre of the line occurs on-trend with the Port Hills Fault which was the locus of many aftershocks in the first 6 months of 2011. A second, minor fault is interpreted towards the north end of the line, and coincides with a gentle fold in the sedimentary section, indicating compression from the north.

Line 2 was recorded in the central city, with a detailed view of the line location is shown in Figure 4.

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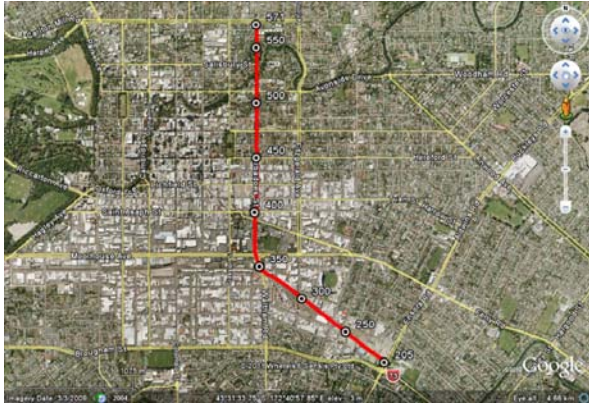


Figure 4. Location of seismic line 2 – through the city of Christchurch (Barbadoes Street). Map data © 2011 Whereis® Sensis Pty Ltd (Google Earth, 2011).

Line 2 is 3.7 km long and was the most challenging of all of the lines surveyed. The southern section trended southeast-northwest and followed a railway line allowance. Challenges along this part of the line included planting geophones and getting good source coupling on the railway ballast. The north-south segment was recorded along Barbadoes Street, a major thoroughfare in the city, although the central 2 km were closed to public access. Challenges along this road included geophone plants in pavement, old sewers and other infrastructure below the road, and the problem of source-points close to damaged buildings and surface infrastructure (Figure 5). Traffic and road-crossings at both the north and south ends of this line also created some difficulties.



Figure 5. Source operating along Line 2, outside the heavily damaged Catholic Basilica, Christchurch.

The migrated section from Line 2 is shown in Figure 6. As in Line 1, it shows a reflection from the top of the Lyttelton volcanics dipping to the north and younger sediments lapping out against this surface. Two old faults are interpreted to have minor offsets in the top volcanic event in this section, but displacements are not observed at the ground surface. Towards the north, a shallow channel is interpreted in an area which was heavily damaged due to liquefaction.

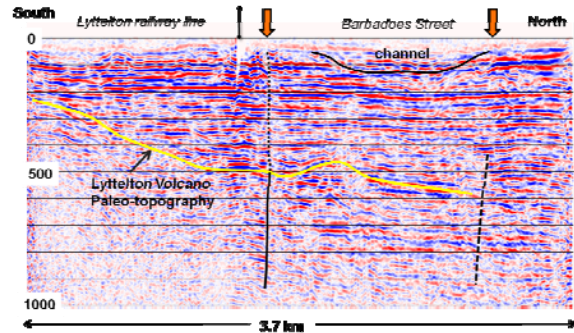


Figure 6. Interpreted seismic Line 1. The Port Hills Fault contains the hypocentre of the Mw 6.3 aftershock.

Line 5 was the first of the seismic lines recorded west of the city, with the goal to provide information about subsurface faults in an area where there is an apparent step-over in epicentres (Figure 2). This line is 16.5 km in length and was laid out along rural roads. Here the shot interval was nominally 20 m, but this was reduced to 10 m near the southern and northern ends of the line, along trend from the pattern of aftershock epicentres associated with the Port Hills Fault from the east, and the Greendale Fault from the west.

Figure 7 shows an interpretation of Line 5. As in Lines 1 and 2, the top of Lyttelton volcanic paleo-topography is evident (yellow horizon) and links to the north with a flat reflector that is likely due to outflows from the volcano. The volcanic sequence is interpreted to thin to the north since deeper reflections are visible in the northern half of the line; these events are not imaged beneath the thicker volcanics to the south. Two families of faults are interpreted in his section. Shallow, recent faulting is prevalent in the south, and deeper older faults are interpreted in the northern part of the line, with significant structure in the acoustic basement.

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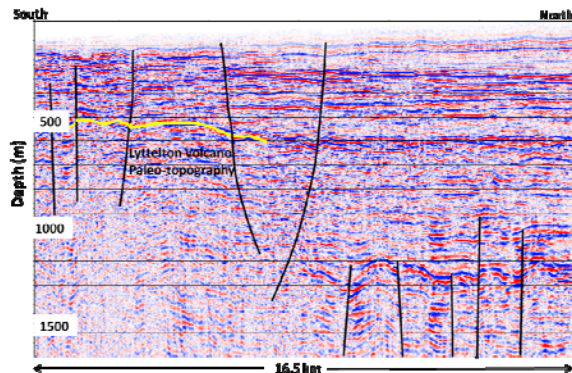


Figure 7. Interpreted Line 5, linking the stepover between the Darfield and Port Hill Fault systems.

The Darfield Mw 7.1 earthquake (Quigley et al., 2010) was located on a previously unknown fault system in the Canterbury region and it generated a nearly 30 km long surface rupture (named the Greendale Fault) across an alluvial plains environment. Detailed strain measurements showed a net maximum displacement of 5 m, made up of ~4.5 m of dextral strike-slip displacement and up to 1.5 m vertical displacement, up-thrown to the south (Quigley et al., 2010). Line 3 was 3.4 km long and was located to cross the Greendale fault near its maximum displacement (Figure 16). The goal was to use this line as a template for other, shallow faults in the area, and to interpret strain rates from displacements of reflectors with known age dates.

Figure 8 shows the interpreted seismic image across the Greendale Fault. The fault zone is quite wide (~200 m) and deeper events show loss of reflectivity within the fault zone. It is interpreted to dip to the north, consistent with observations from moment tensor analysis of the fault displacement and fault plane orientation (Quigley et al., 2010). The increasing reflector offset with depth suggests that this fault has indeed been active in the geological past, even though no surface evidence for it has been documented throughout the time that this region has been settled. The deep reflector (1200 m) also has an older fault interpreted to offset it, creating a horst feature.

Conclusions

The seismic program in the Christchurch region has successfully delineated a number of faults that were previously unknown. The general pattern of the fault systems in the area is shown in Figure 19, identified by the dashed white lines. Only the Greendale Fault ruptured to surface (solid white line). The faults identified through the seismic program are interpreted to be near-surface (< 1.5 km) expressions of deeper faults that are the loci of

aftershock hypocentres shown in Figure 19. The hypocentre of the Darfield Earthquake is reported to be at a depth of 10.4 km (Gledhill et al., 2011).

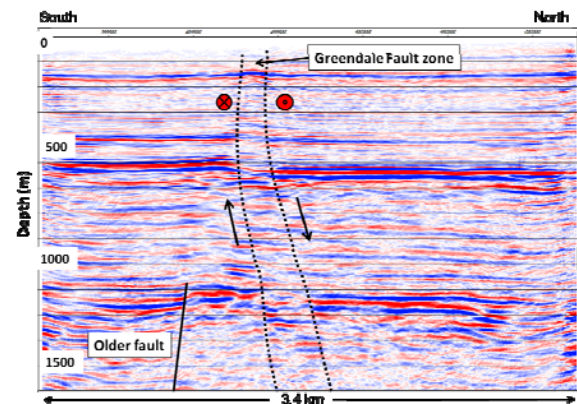


Figure 8. Interpreted seismic section from Line 3 (Greendale Fault)

Linkages within the fault systems and step-overs between fault segments will be the topic of future studies. Fault segmentation has been documented by many researchers, with the majority of initial studies focussed on normal faults. Peacock and Sanderson (1991) examined fault segment linkage and relay ramps associated with normal faults, and Peacock (2002) extended this work to include both propagation and kinematics of normal faults. Both of these studies were based on field mapping and structural models. Kristensen et al. (2008) examined relay zones between normal faults in soft sediments at scales of centimetres and showed that relay zones become breached by propagation of the initial fault. Marchal et al. (2003) examined normal fault geometries in outcrop studies (2D) and also from seismic interpretation (3D) and studied fault evolution in physical modelling studies, and identified secondary structures developing as isolated faults propagate towards each other.

Acknowledgements

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EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2012 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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