

Post-earthquake seismic reflection survey, Christchurch, New Zealand

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ABSTRACT

Approximately 41 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 that caused the loss of 182 lives. The recording system used was the 600-channel Aram Aries system and EnviroVibe belonging to the Department of Geoscience at the University of Calgary. 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. Equipment preparation and field recording in New Zealand was undertaken by CREWES staff on a full cost-recovery basis.

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 shallow after-shocks in the region. These interpretations are now being incorporated into a risk assessment for further possible shallow earthquakes in the region.

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 to the city infrastructure, buildings and homes. Since September, 2010, the region has experienced over 9000 aftershocks, with 2662 of these being greater than 3M.

In collaboration with scientists from the University of Canterbury in Christchurch, a proposal to the New Zealand Government was submitted in late 2010 to record seismic profiles around the city to better understand the fault systems beneath that city, as this

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part of the country had previously been thought to have a low earthquake risk. Soon after the February 22, 2011 earthquake struck, a request was received from the NZ Crisis Management Centre to mobilise the Department of Geoscience's 600-channel Aries seismic recording system and Envirovibe to New Zealand to undertake urgent seismic profiling in and around Christchurch to assist in identifying shallow fault systems for earthquake risk assessment and natural hazard identification. The CREWES team at the University of Calgary scrubbed clean the recording system and EnviroVibe which were then airfreighted by courier to New Zealand. Figure 1 shows the vibe harnessed to a rack that was placed in a Boeing 747 heavy-lift aircraft for the trip. Full details of the acquisition program and logistics are provided by Hall et al. (2011).

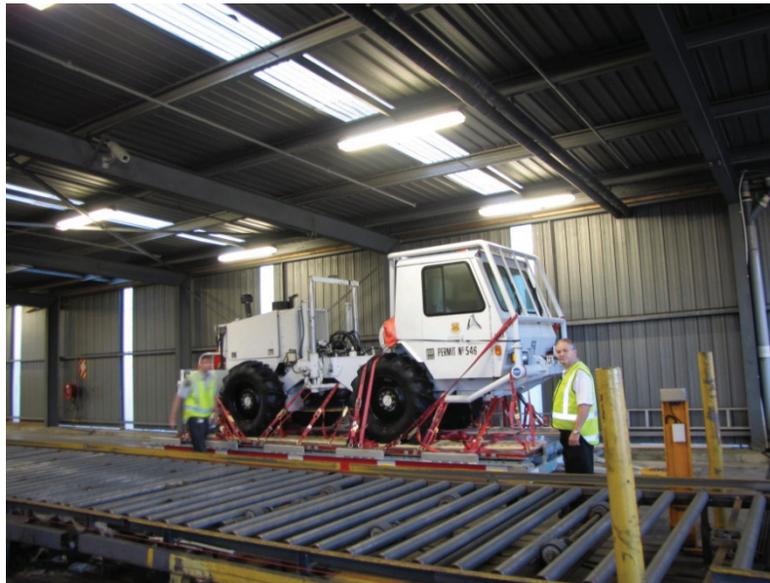


FIG. 1. Envirovibe lashed to shipping rack for flight to New Zealand

REGIONAL TECTONICS

New Zealand lies in a tectonically active area and straddles the boundary between the Australian and Pacific plates. Figure 2 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 $M_w > 6$ are also shown. Those greater than $M_w 7$ 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 3 shows a geology map of the Canterbury region, showing previously known faults in the west and north of the region, as well as the Greendale Fault that ruptured during the $M_w 7.1$ Darfield Earthquake on September 4, 2010. The epicentres of the 9008 events recorded since September 4, 2010 are shown in Figure 4.

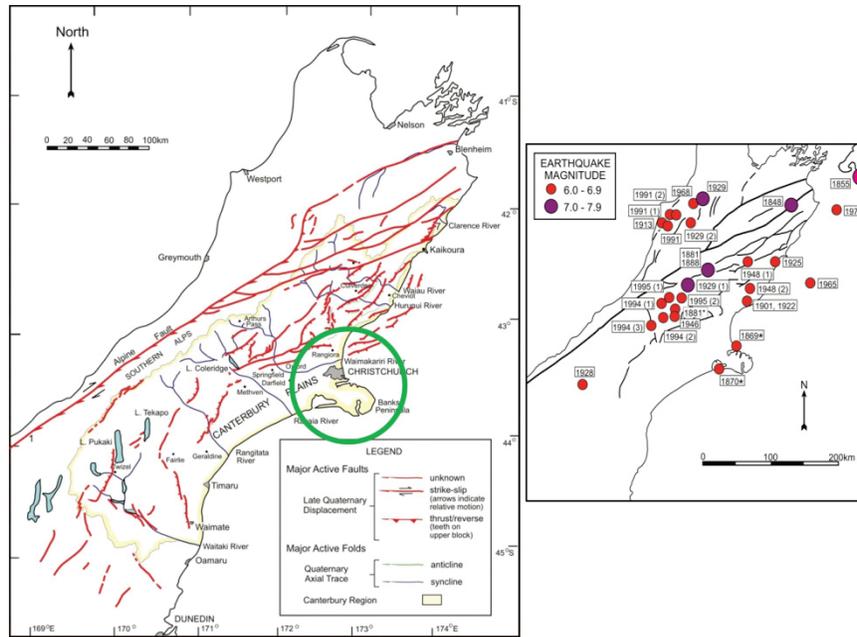


FIG. 2. Tectonic map of the South Island, New Zealand (after Pettinga, 1986).

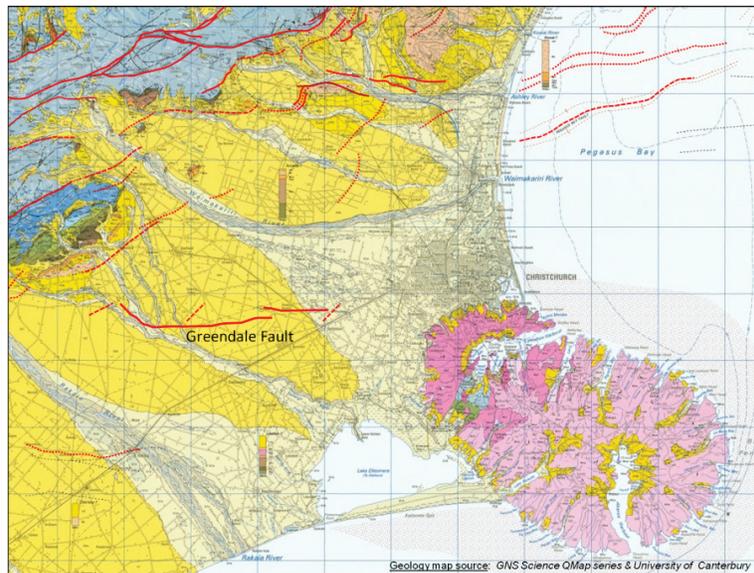


FIG. 3. Geology map of Canterbury region showing faults in red. The Greendale Fault ruptured during the September 2010 Mw 7.1 earthquake (courtesy GNS Science).

DATA ACQUISITION

The recording team of Malcolm Bertram, Kevin Hall, Kevin Bertram and Don Lawton made two trips to Christchurch through April and May of 2011 and recorded over 40 line km of high-fold 2D seismic data to map faults below the city. The layout of the seismic lines is shown in Figure 5. 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.

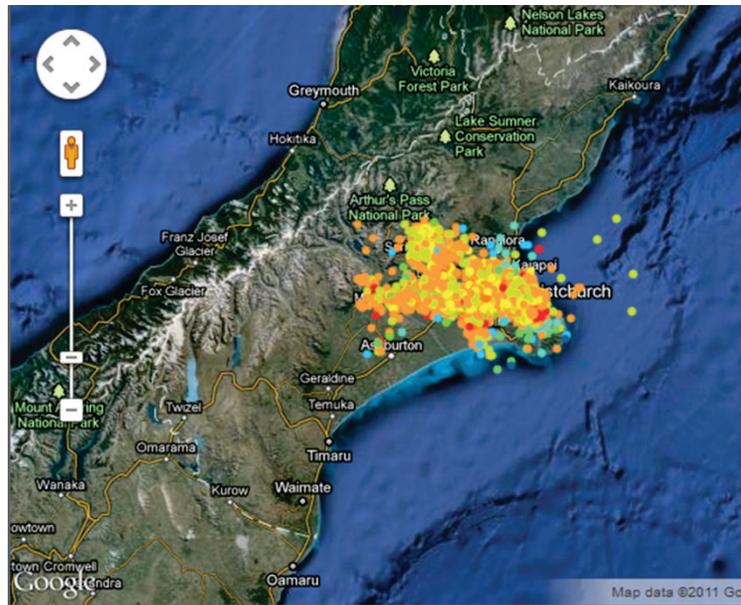


FIG. 4. Epicentres of 9008 events recorded in the Christchurch region since September, 2010. Colour denotes hypocentre depth (ranging from < 2.5 km in red, to > 25 km in light blue). Map data © 2011 Europa Technologies and © 2011 Google and © 2011 Whereis® Sensis Pty Ltd. Imagery © 2011 NASA and © 2011 Terrametrics (Christchurch Quake Map, 2011).

This region of the city was closed to public access because of damage and proximity to unstable buildings. Lines 3 and 5 through 7 were recorded west of the city to investigate ‘step-overs’ in the pattern of shallow epicentres (Line 4 was omitted from the survey).

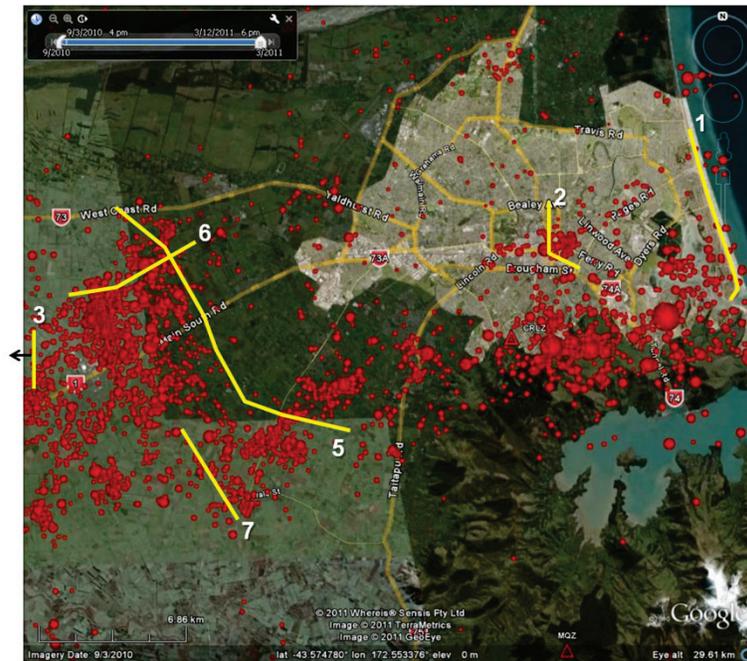


FIG. 5. Layout of 2D seismic lines recorded during the Christchurch seismic program. Red dots show the epicentres of aftershocks through to June 2011 (GNS Science). Line 3 was located 10 km further to the west of position shown. Map data © 2011 Europa Technologies and © 2011 Google and © 2011 Whereis® Sensis Pty Ltd. Imagery © 2011 NASA.

Line 3 was located further to the west, and crossed the surface trace of the Greendale Fault that ruptured in the September 2010 earthquake (Figure 3). Recording parameters of the seismic survey are summarised in Table 1 following tests carried out on Lines 1 through 3.

Table 1. Seismic acquisition parameters, Christchurch seismic survey

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
Recording system	600-channel ARAM Aries

The data were processed by Sensor Geophysical in Calgary, following a standard processing flow. Particular attention was paid to refraction statics and noise attenuation, particularly for lines recorded along the beach (Line 1) and in the city (Line 2). Some additional processing has been undertaken by CREWES personnel.

DATA INTERPRETATION

Interpretations of the seismic lines are presented in order from east to west.

Line 1

This was the first line recorded during the survey and the line is located along the Pacific Ocean beach on the east side of the city (Figure 6). It was 8 km in length.



FIG. 6. Recording the seismic line along New Brighton Beach, Christchurch. Recorder van is in left picture and geophone spread is in the foreground of the picture on right.

The goal of this line was to image faults that, from aftershock data, were inferred to cross the beach along this line. Recording had some challenges, with soft sand, wave noise and an unexpected tidal surge which drowned the line one evening. Fortunately, the line came up live next day with few issues other than buried geophones and cables, and seaweed entanglements.

The interpreted seismic line from Line 1 is shown in Figure 7. 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 (shown in red colour in Figure 3). 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.

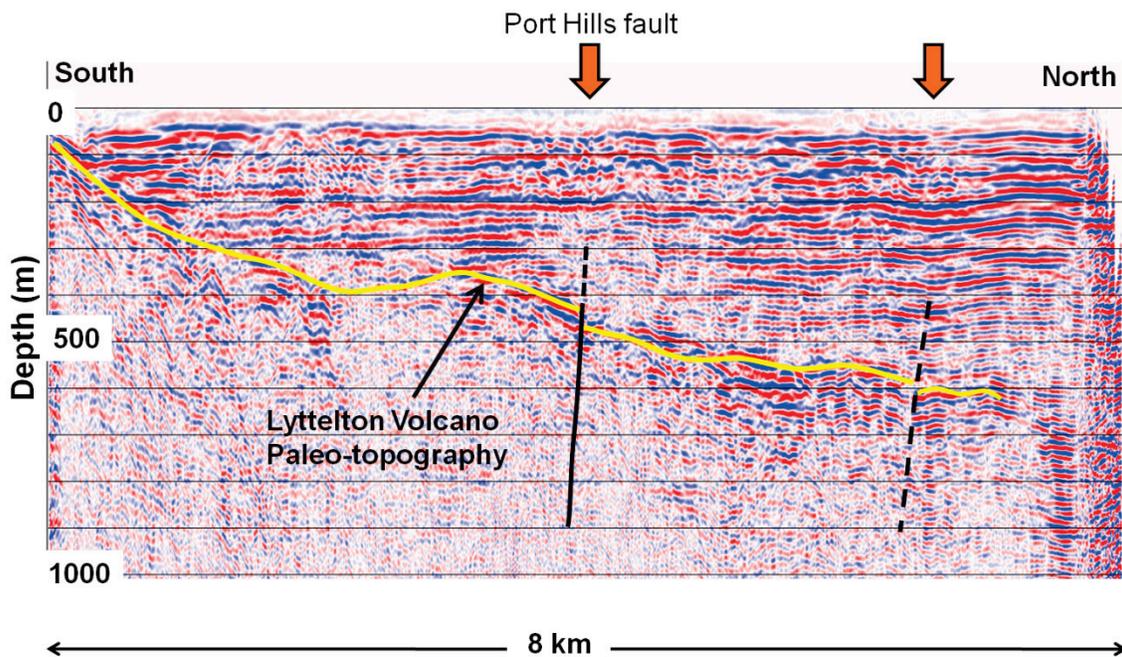


FIG. 7. Interpreted seismic Line 1, along New Brighton Beach.

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. 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

This line was recorded in the central city (Figure 3), and a detailed view of the line location is shown in Figure 8.

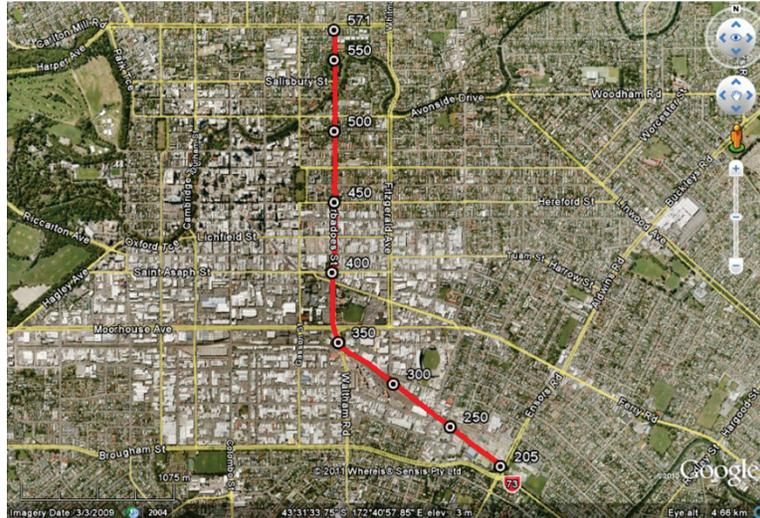


FIG. 8. Location of seismic line 2 – through the city of Christchurch (Barbadoes Street). Map data © 2011 Whereis® Sensis Pty Ltd (Google Earth, 2011).

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 9). Traffic and road-crossings at both the north and south ends of this line also created some difficulties.



FIG. 9. Seismic acquisition along Barbadoes Street, Christchurch. Geophone plant (left) and source-point outside damaged Catholic Cathedral (right).

The migrated section from Line 2 is shown in Figure 10. As in Line 1, it shows a reflection from the top of the Lyttelton volcanic 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.

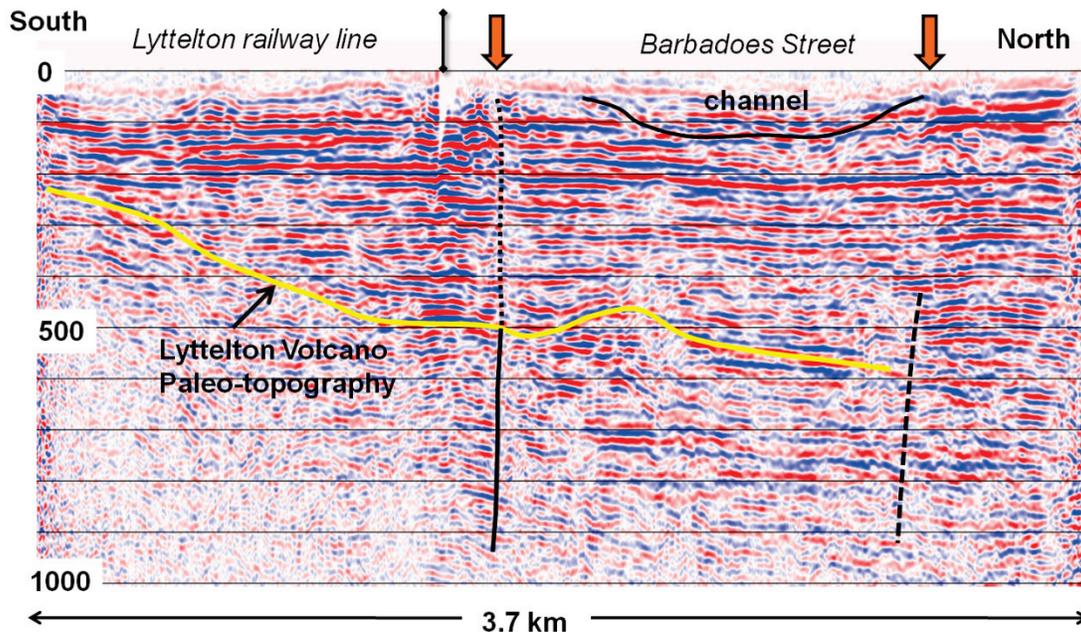


FIG. 10. Interpreted seismic Line 2, along Barbadoes Street

Line 5

Line 5 was recorded along Robinsons Road and 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 5). This line is 16.5 km in length and was laid out along rural roads. Cable crossing of many roads, including State Highway 1 (the main north-south road in the South Island) was accomplished by threading the cable through convenient irrigation culverts that ran under the roads. Along Line 3, 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 11 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 this 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.

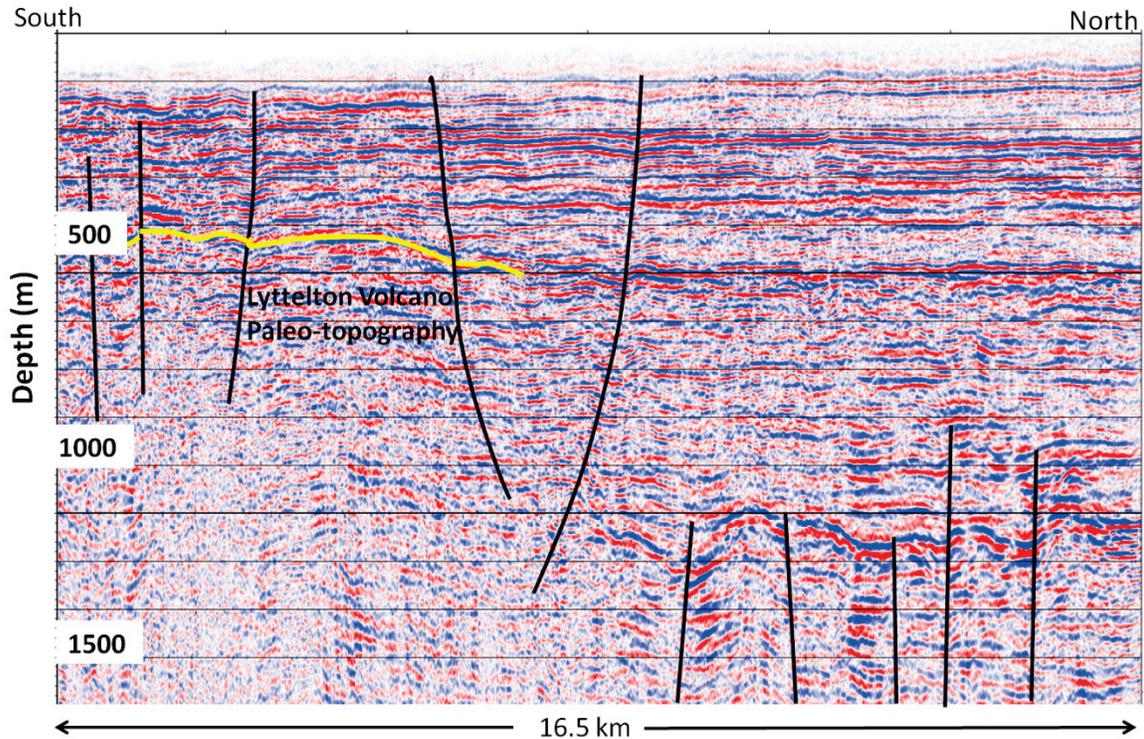


FIG. 11. Interpreted Line 5, linking the stepover between the Darfield and Port Hill Fault systems.

For a more detailed view of these sections, the line was divided into 3 segments, as located in Figure 12. Figure 13 shows the southern, middle, and northern segments of Line 5.



FIG. 12. Line 3 segments for detailed interpretation. Map data © 2011 Whereis® Sensis Pty Ltd (Google Earth, 2011).

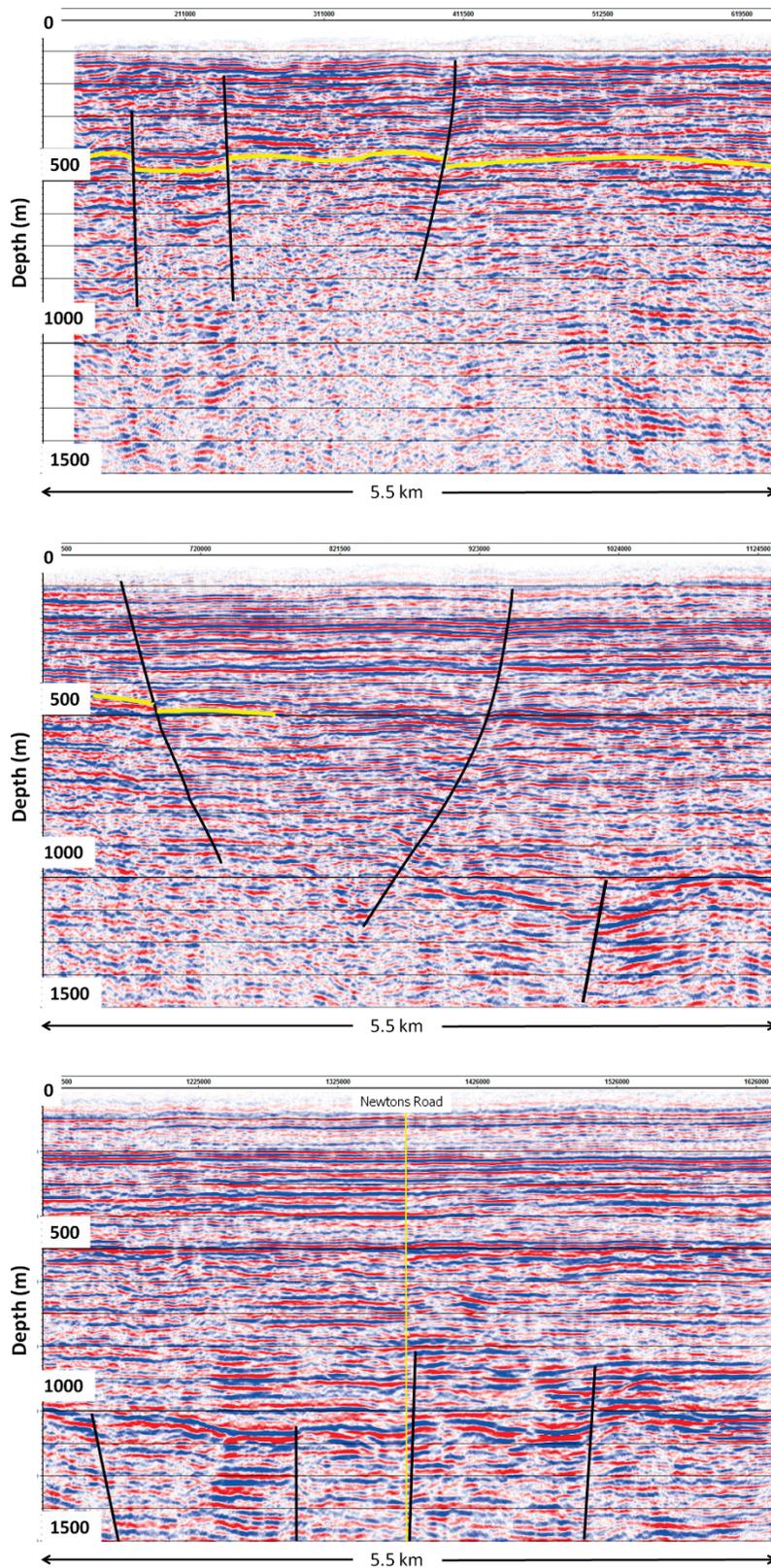


FIG. 13. Segments of Line 5 for detailed interpretation; southern section (top), central section (centre) and northern section (bottom). All sections are south to north from left to right. Tie with Line 6 is shown by the yellow line in the bottom figure.

In terms of risk, the fault in the centre of the seismic line, with a dip to the south, is most significant (Figure 13, centre). This fault has experienced recent activity with the graben feature in the line (Figure 13, centre) showing very shallow displacements in near-surface reflectors. The epicentre of a recent aftershock was located on this fault.

Line 6.

This line was located along Newtons Road and was orthogonal to Line 5. It was designed to elucidate, if possible, the 3D geometry of faults in the northern region of the seismic coverage. The interpreted section is shown in Figure 14. Data quality was good and an excellent tie was obtained with Line 5 at the intersection of Newtons and Robinsons Roads. Shallow (< 500 m) reflections (Figure 14) dip gently to the east, toward the depocentre of the young basin. The high-amplitude reflection at ~500 m depth is interpreted to be from outflow deposits of the Lyttelton Volcano. Deeper reflections dip more steeply to the east and 3 faults are interpreted. The lack of clear fault cut-offs and the overlapping behaviour of some of the deeper, discontinuous reflections suggests that the fault trend is oblique to the line of section.

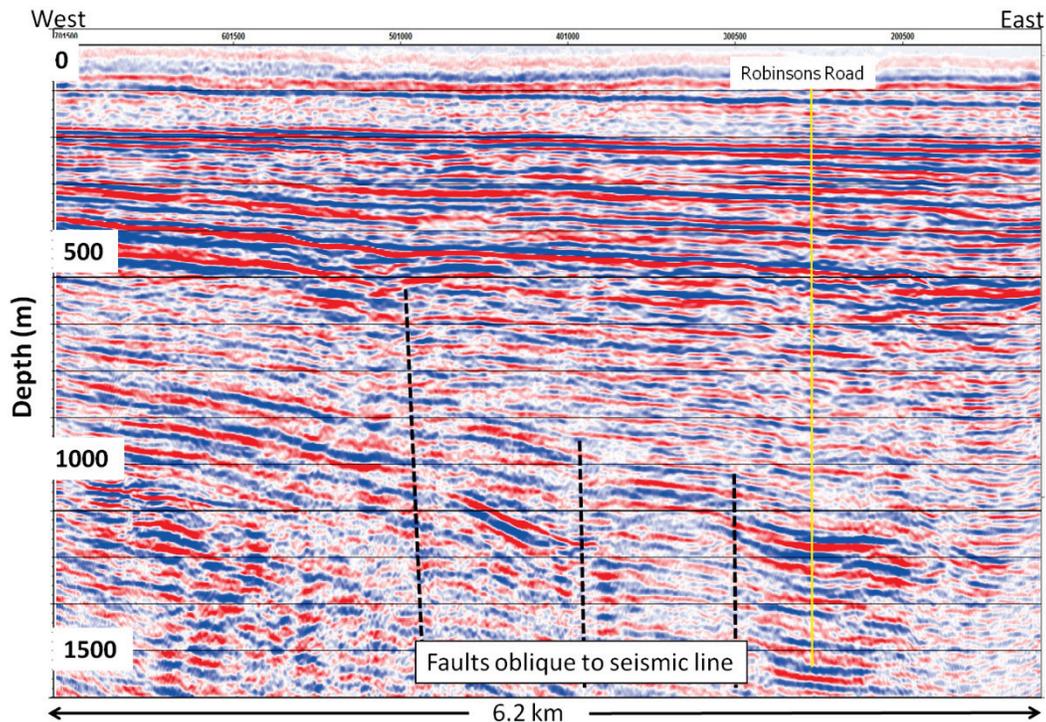


FIG. 14. Interpreted seismic section from Line 6 (Newtons Road). Tie with Line 5 shown (yellow).

Line 7

Line 7 was 4.8 km in length, located along Weedons Road. The goal of this line was to map the possible extension of the Port Hills Fault and related fault systems further to the west. Two faults were interpreted along this line (Figure 15), but offsets of reflections across the faults are generally small and do not appear to reach the present ground surface. However, the fault near the centre of the line shows possible incipient displacement into the shallow section (above the Lyttelton volcanic surface at ~500 m

depth), and loss of very shallow reflectivity above this fault is interpreted to be evidence of liquefaction which was known to occur along this line during the Darfield earthquake.

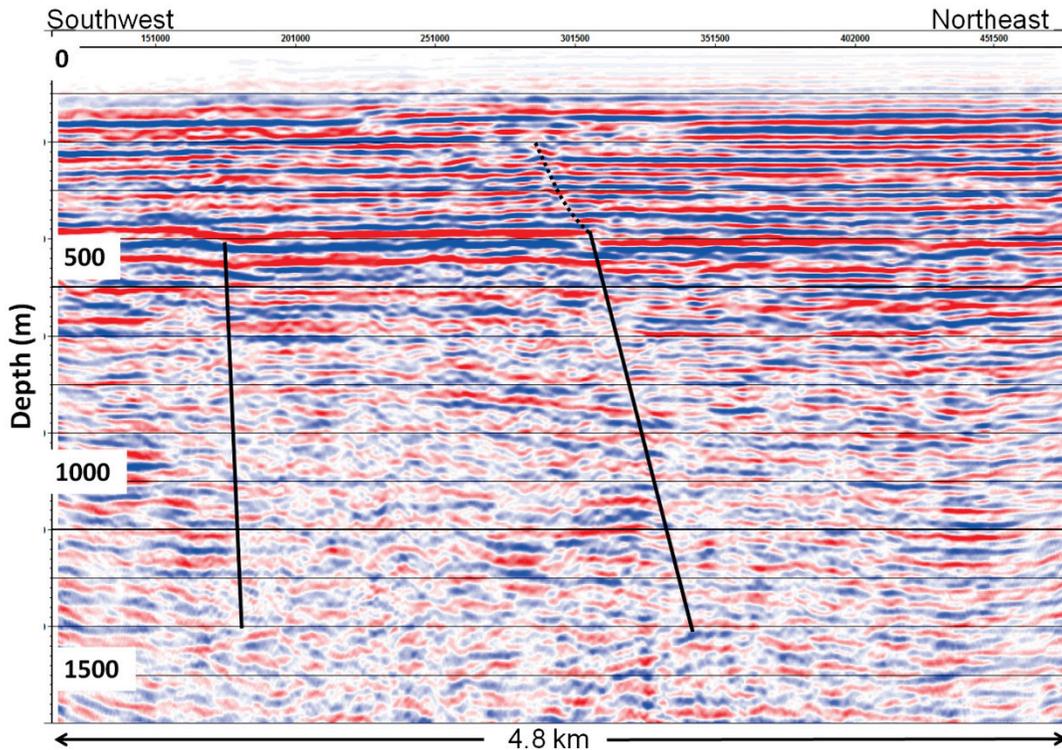


FIG. 15. Interpreted seismic section from Line 7 (Weedons Road).

Line 3

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). Figure 16 shows a view along Highfield Road, across the fault, clearly showing both lateral and vertical displacements. The fault ruptured in at least 3 segments in an *en echelon* pattern with step-over offsets between fault segments of up to 900 m. Line 3 was 3.4 km long and was recorded during the first phase of acquisition. It 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 attempt to interpret strain rates from displacements of reflectors with known age dates.

Figure 17 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.



FIG 16. View along Highfield Road. showing lateral & vertical offsets across the Greendale Fault.

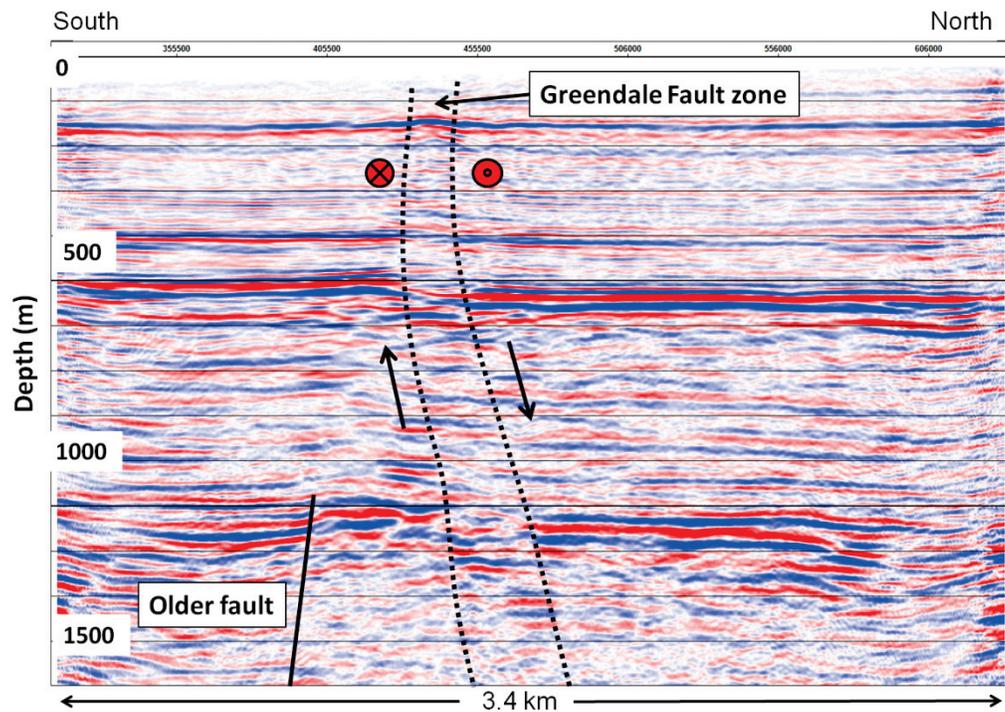


FIG. 17. Interpreted seismic section from Line 3 (Highfield Road).

One explanation for the observed width of the Greendale fault zone is illustrated in Figure 18. This shows a photograph of the Greendale fault surface rupture soon after the earthquake, showing several parallel to sub-parallel faults (red) linked by Riedel shears (yellow). Riedel shears are commonly found in transpressional environments and develop as a result of simple shear during the early stages of fault development (Katz, et al., 2002).

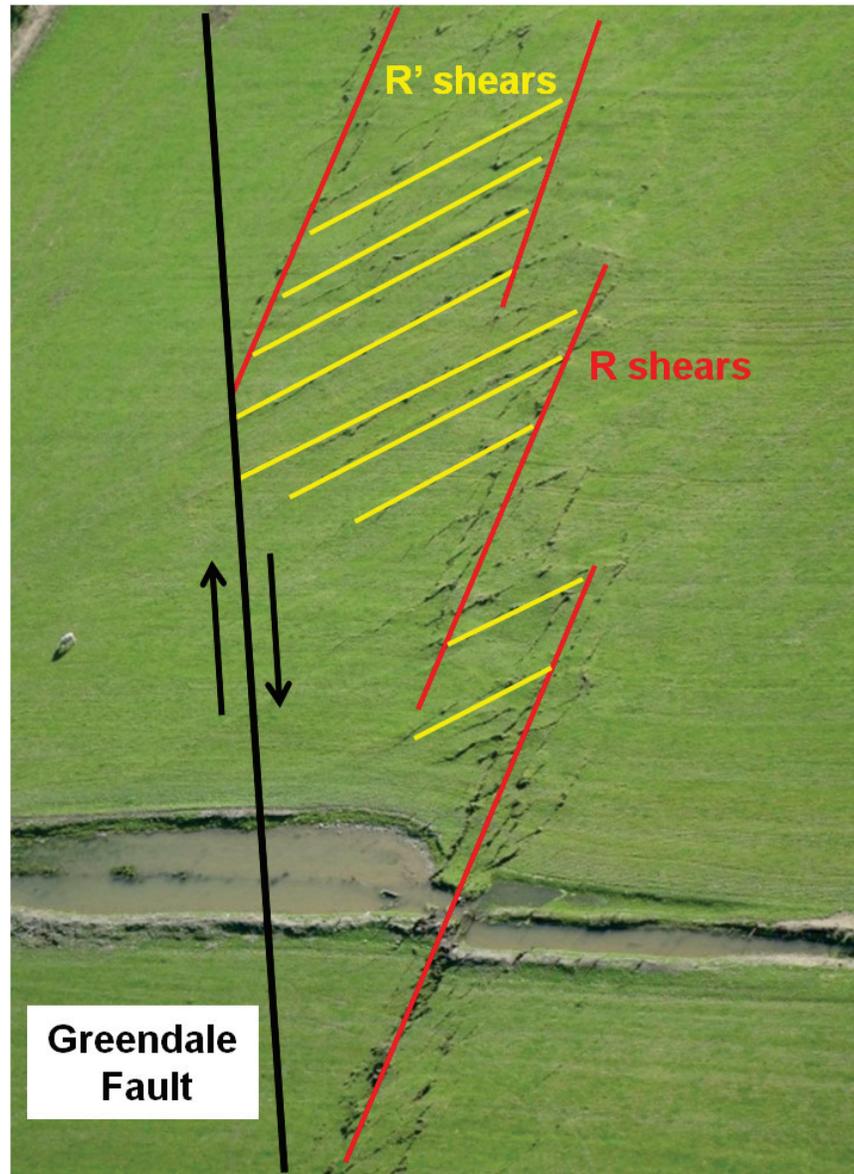


FIG. 18. Greendale Fault and conjugate Riedel shears R and R' (after Quigley et al., 2012).

If deformation continues, the fault system commonly forms a flower structure, where the individual fault segments tend to merge at depth. On Line 6, the fault zone tends to widen slightly with depth, so the individual faults must merge at significantly greater depths than imaged on the seismic data.

DISCUSSION AND 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).

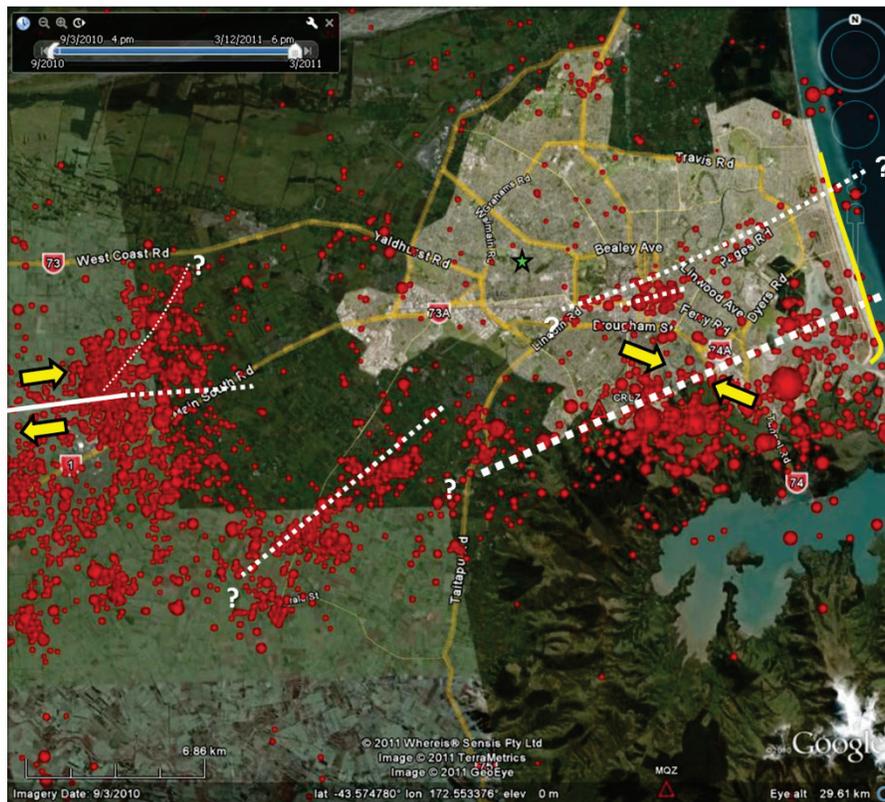


FIG. 19. Fault systems in the Christchurch area interpreted from the seismic reflection survey and the distribution of aftershock epicentres, shown by the filled red circles. Map data © 2011 Europa Technologies and © 2011 Google and © 2011 Whereis® Sensis Pty Ltd. Imagery © 2011 NASA

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

Funding for this project was provided by the New Zealand Crisis Management Centre, the Institute of Geological and Nuclear Sciences, a crown research institute in New Zealand, and the University of Canterbury. We particularly thank Mike Finnemore (Southern Geophysical) and students from the University of Canterbury for field and logistics support. We thank GEDCO for providing software for in-field quality control and initial processing. We thank and appreciate the contribution of Sensor Geophysical for kindly donating the full processing of data collected during Phase I of the program (Lines 1 through 3).

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