SOURCES, GROUND MOTION AND STRUCTURAL RESPONSE CHARACTERISTICS IN WELLINGTON OF THE 2013 COOK STRAIT EARTHQUAKES

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SUMMARY

The Cook Strait earthquake sequence occurred in a region of known high seismicity. However, this was the strongest shaking felt in decades for the Wellington region and the top of the South Island. The location and size of the earthquake meant that the ground shaking was of rather short duration and moderate intensity, except for the epicentral region of the Lake Grassmere earthquake where a PGA of 0.7g was recorded, and for part of the Wellington foreshore where up to 0.2g was recorded in both earthquakes. The level of shaking in terms of response spectra was, in general, moderate except for very high "spiked" response at particular Wellington sites (WNKS and VUWS) at periods of 0.4-0.5 seconds. Amplification and polarization in the NE-SW direction at approximately ~1 s period at many Wellington stations is likely due to basin resonance effects, whereas dominant polarization in the NW-SE direction at shorter periods is consistent with a directivity effect, and is particularly evident in the Lake Grassmere earthquake. The earthquakes were not only a real-life test on the level of preparedness for the population but also on the behaviour of recently-built structures in the Wellington region that had not yet experienced a moderate earthquake. The ability to measure, analyse and understand the intensity and characteristics of the ground shaking coupled with well-documented damage to the buildings and building array recordings will hopefully foster collaboration across earthquake engineering disciplines.

THE COOK STRAIT EARTHQUAKES

The 2013 Cook Strait earthquake sequence produced the most significant ground shaking in the Wellington and Marlborough regions in recent decades. The sequence began on 19th July, 2013, at shallow depths offshore from Seddon (Fig. 1). Two foreshocks of M_w 5.5 and M_w 5.8 preceded the M_w 6.6 Cook Strait earthquake on 21st July. The major events of the sequence showed a general south-westward progression, with the M_w 6.6 Lake Grassmere earthquake following on the 16th August, in the onshore region.

In the paragraphs that follow we give a brief overview of the Cook Strait earthquake sequence, including tectonic setting, ground motion observations, preliminary source models, and general impression regarding impacts on engineered structures.

REGIONAL TECTONICS AND SEISMICITY

The Cook Strait earthquakes occurred in a region of recurrent seismicity marking the transition along the New Zealand plate boundary from oblique subduction in the southern North Island to strike-slip faulting through Marlborough (e.g., Wallace *et al*. 2012). The epicentral region is characterized by historically high levels of seismicity and several major active fault structures including the west-dipping subduction interface at ~25 km depth (e.g., Stirling *et al*. 2012, Litchfield *et al*. in press). In 2005 the area was the location of a swarm of M4+ earthquakes, and prior to that it was also the site of the 1977 Cape Campbell earthquake (M ~6) and the 1966 Seddon earthquake (M ~5.8) (e.g., Downes & Dowrick 2012). Larger historical earthquakes have also occurred nearby in 1855 on the Wairarapa Fault (e.g., Grapes & Downes 1997, Little *et al*. 2009) and in 1848 on the Awatere Fault (e.g., Grapes *et al*. 1998, Mason & Little 2006).

To date, seismicity of the Cook Strait sequence has largely occurred on unmapped structures at depths of 6 – 18 km, and generally follows a northeast-southwest trend (Fig. 1). Seismicity is mainly concentrated in the region above the subduction interface and between the Awatere Fault to the northwest, the London Hill Fault to the southeast, the Clarence Fault to the southwest and the Wellington Fault to the northeast (Fig. 1). Further studies including double difference relocations, seismic tomography and analysis of stress and strain from small earthquakes will provide further tectonic context for the 2013 earthquake sequence (Reyners 2013).

THE JULY 21ST M_W 6.6 (M_L 6.5) COOK STRAIT EARTHQUAKE

The Cook Strait earthquake occurred only two days following a foreshock sequence of magnitude 5+ events. The epicentre was located offshore, about 10 km southwest of the foreshock location and 50 km away from Wellington. Wellington CBD suffered minor structural damage but the timing of the earthquake (Sunday evening) meant that there was little disruption to the city. However, due to necessary building inspections, the CBD was shut down all of Monday morning and most of Monday afternoon.

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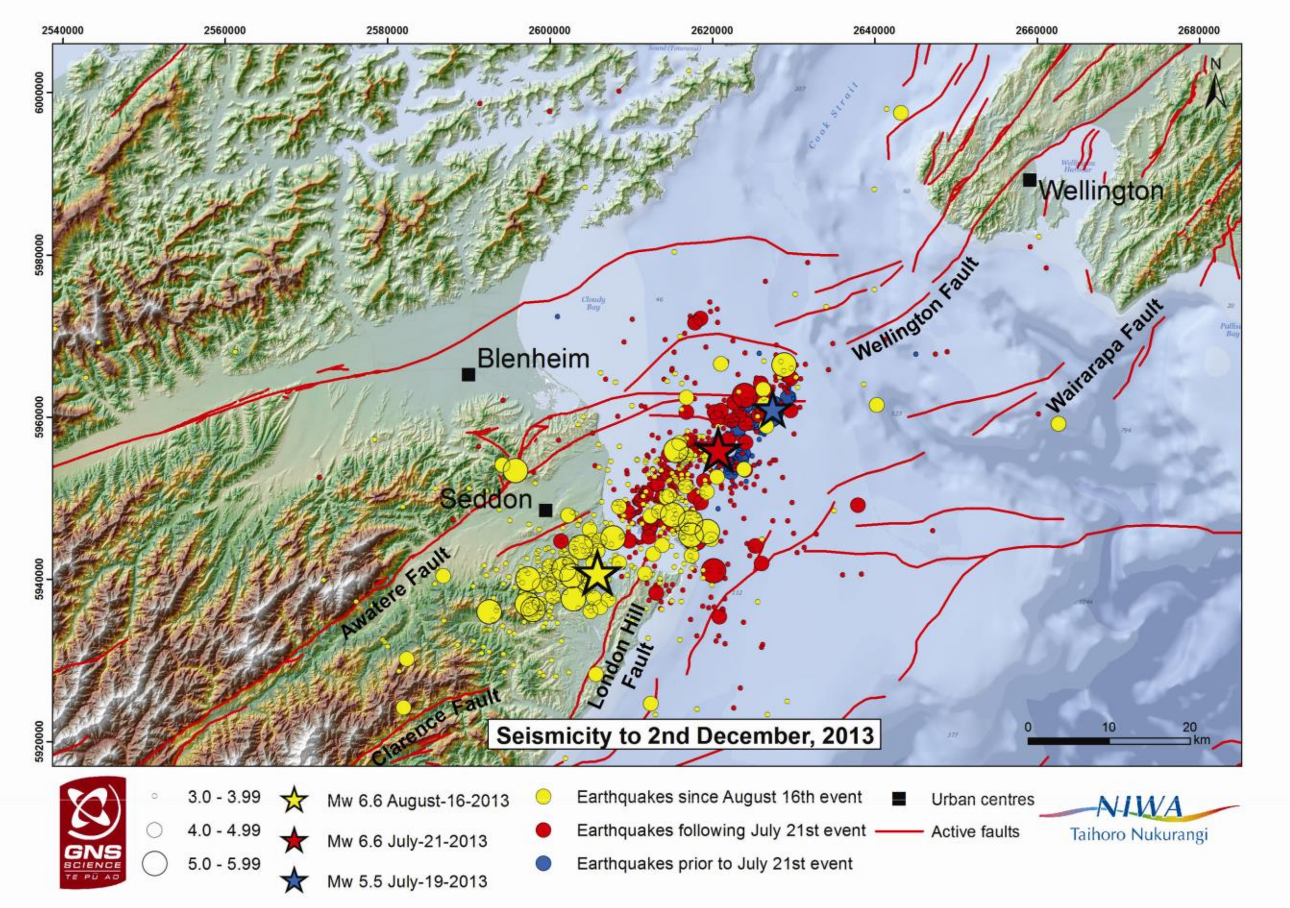

Figure 1: ***The 2013 Cook Strait earthquake sequence, to date, comprising a M_W 5.5 foreshock on 19 July, 2013, the M_W 6.6 Cook Strait earthquake on 21 July, the M_W 6.6 Lake Grassmere earthquake on 16 August and many accompanying aftershocks. The epicentral region is characterized by historically high levels of seismicity and several major active fault structures including the west-dipping subduction interface at ~25 km depth. The seismicity to date has largely occurred on an unmapped structure at depths of 6 – 18 km, and generally follows a northeast-southwest trend. (For more information see Reyners (2013)).***

Ground motion observations and source model

The region was well-instrumented with over 50 strong-motion sensors from the GeoNet network within 200 km of the epicenter (not including instrumented buildings mentioned later on).

The strongest readings for the Cook Strait earthquake were approximately 0.26g at Ward (about 16 km southeast of the epicentre) as well as in central Wellington (Figure 2). Shaking duration in central Wellington was short (moderate shaking (above a 0.02g threshold) lasting 6 seconds and 7 seconds for WNKS and VUWS sites respectively).

We modeled ground motion history for the Cook Strait earthquake using near source GeoNet strong motion stations, in much the same fashion as Holden (2011) did for the M_w 6.2 Christchurch earthquake in the 2010-2011 Canterbury earthquake sequence. This solution is constrained onto a fault plane obtained by modeling GPS and InSAR data (see Hamling *et al*. 2013 for more details). The preliminary kinematic solution suggests slip on a near-vertical fault plane striking NE-SW with up to 1 m of slip at a depth of about 12 km (Fig. 3). The model also suggests a bilateral rupture, supporting the lack of significant directivity effects.

Response spectra analysis

In central Wellington, spectral accelerations at a number of locations ranged up to 30% of the current building design level for any given subsoil site class and periods ranging between 0.4 and 1 seconds (Fig. 4).

Recorded response spectra were particularly large at the Victoria University Building site (VUWS) close to the harbour foreshore, and areas of reclaimed land, where motions were over 50% the design level at periods of 0.4-0.5 seconds. The Karori Normal School site (WNKS), further inland and into the hills, also responded strongly with recorded levels up to 100% of the design level at 0.4 seconds (Fig. 4). It is worth noting that this peak record level is only apparent over a very narrow period range indicative of a local site effect, and that the overall spectral response at short periods is on average closer to 30% of the design level. Bradley (2013) also provides an overview of ground motion characteristics from the Cook Strait earthquake.

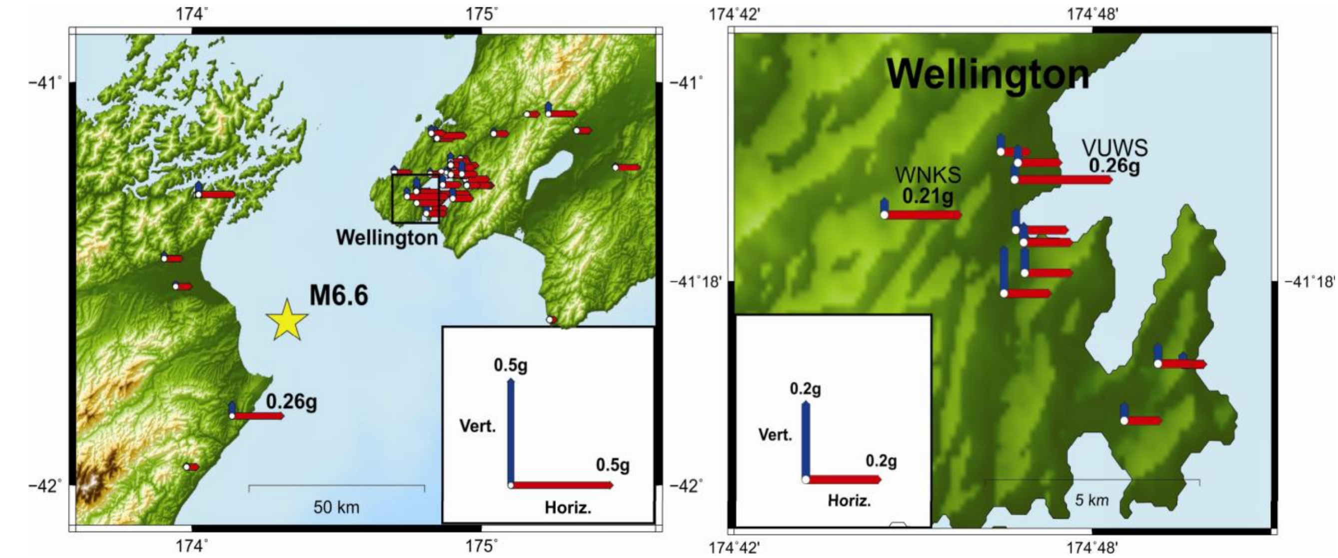

Figure 2: ***Observed peak ground acceleration (PGA) at GeoNet stations during the Mw 6.6 Cook Strait earthquake (epicentre is shown as yellow star). Location of right figure detailed in left figure, and note the change of scale between the two figures.***

An additional broader peak or 'bump' in spectral acceleration at ~1 second period is observed at many Wellington sites, most strongly at those located on deep soil within the basin (TEPS, FKPS, VUWS, WEMS, RQGS), but also at stations near the basin edge (WNHS, POTS). This amplification is most likely due to basin resonance effects. Preliminary analysis of the polarization of ground motion (illustrated in the polar plots in Figure 4) indicates a SW-NE polarization of the response spectra at ~1 second period at these stations. This is consistent with a dominant polarization direction previously inferred within the Wellington-Hutt Valley basin (Benites & Caldwell 2011). Secondly, the polar plots also show a large amplification response of the response spectra at 0.4 seconds in the NW-SE directions for stations WNKS and VUWS.

THE AUGUST 16TH M_W6.6 LAKE GRASSMERE EARTHQUAKE

The Lake Grassmere earthquake occurred nearly 4 weeks after the Cook Strait earthquake. The epicentre was located onshore, almost directly under Lake Grassmere, and further away from Wellington (about 80 km southwest) (Fig. 1). However, for population in the South Island near the epicentre the earthquake impact was very strong and the experience very frightening. Many homes in Seddon were badly damaged and then endured very heavy rainfalls that caused water damage to structurally compromised houses. In Wellington, the timing of the earthquake (a weekday afternoon) now imposed some disruption to the city. Residents of Wellington city were eager not only to get their car out of building car parks as soon as possible (possibly recalling that some car park buildings were still closed to the public since the Cook Strait earthquake), but also to get back and check on their family. For Wellington, this event was a real-life test for how well-prepared people were for a future major event.

Ground motion observations and source model

The earthquake was again well recorded by a wealth of strong motion stations from the GeoNet network now including extra stations deployed as part of the response to the Cook Strait earthquake (Figs. 5 & 6). It was also recorded by a temporary array of low-cost MEMS accelerometers linked to the global Quake-Catcher Network (Cochran *et al.* 2009; Kaiser *et al*. 2011).

PGA of over 0.7g was recorded 6 km from the epicenter at a temporary GeoNet site near Seddon. PGA of up to 0.67g was recorded in Ward and 0.14g in Blenheim. In Wellington city, GeoNet instruments recorded PGAs up to 0.2g. However shaking duration in central Wellington was again short with moderate shaking (above a 0.02g threshold) lasting for 3 seconds and 4 seconds for WNKS and VUWS sites, respectively.

Based on the fault plane modeled from GPS and InSAR data (Hamling *et al*. 2013), we tested a range of kinematic source models to best fit the strong motion data at near-source GeoNet stations. The proposed kinematic model of the Lake Grassmere quake (Figure 7) suggests a maximum slip of 2.8 m at 7.2 km depth; shallowest slip is 0.25 m at 1 km depth, consistent with the observation of no ground-surface fault rupture (Van Dissen *et al*. 2013). This model suggests a strong directivity effect with the earthquake rupturing from southwest to northeast towards Wellington. The directivity effect is supported by simple observations of the fault-normal and fault-parallel shaking characteristics from a range of well-distributed sites as observed by R. Benites (GNS Science) and illustrated in Figure 6: strong S phases are observed in the Wellington region northeast of the rupture, but not at many of the South Island stations.

Response spectra analysis

In central Wellington a number of stations recorded spectral accelerations up to 20-30% of the current building design level for any given subsoil site class and periods ranging between 0.4 and 1.2 seconds (Fig. 8).

Recorded spectra were again high for VUWS where levels reached 50% of the design level at 0.5 seconds, and at the Karori Normal School site where recorded levels were again found to be approximately 100% design level at 0.5 seconds (Fig. 1). Again, it is worth noting that this peak record level is only apparent over a very narrow period range indicative of a local site effect (e.g. Kaiser *et al.* 2013) and that the overall spectral response at short periods is on average closer to 30-50% of the design level. Ma and Wotherspoon (2013) also provide an analysis of the response spectra in relations to the soil condition for the Grassmere earthquake.

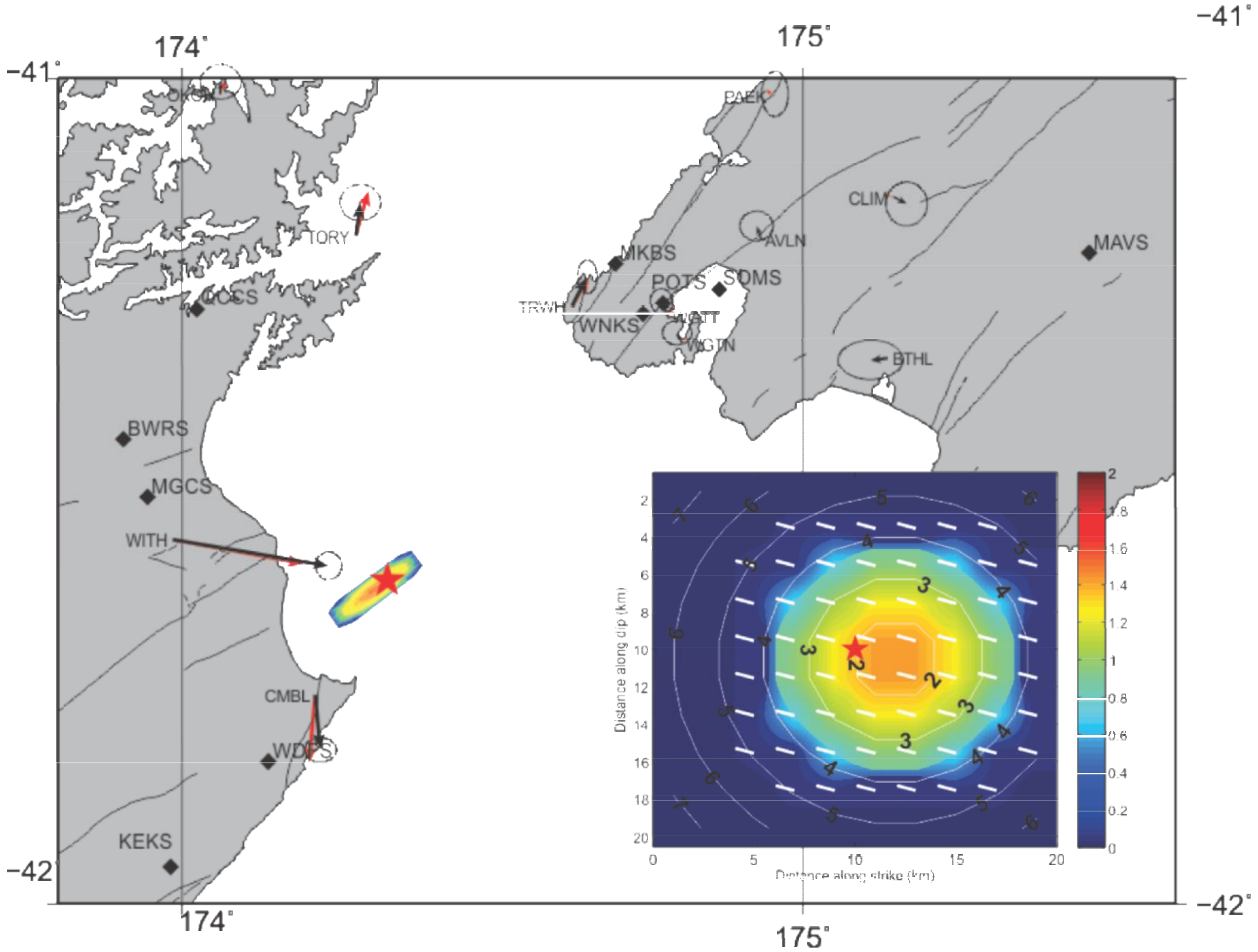

Figure 3: ***Preliminary slip history for the Cook Strait earthquake resolved onto a 18 by 12 km near-vertical fault plane striking NE-SW with up to 1 m of slip at a depth of about 12 km and a bilateral rupture. Fault parameters are strike 234, dip 75 degrees, rake 164 degree, rupture velocity 2.2 km/s. The black and red arrows are measured and observed ground displacement respectively following the Cook Strait earthquake (Maximum of displacement at WITH moving 5 cm to the East). The inset shows the rupture history on the fault plane looking from the North: the rupture time contours are in white isochrones, the red star is the GeoNet hypocentre location and colours represent slip amplitudes (scale in metres). This model does not suggest any particular directivity effect.***

Preliminary analysis of the response spectra polar plots (Figure 8) suggests a strong polarization of the signal at ~0.5 second period in the NW-SE direction at most Wellington stations including POTS, WNKS, VUWS and FKPS. This polarization direction is consistent with the occurrence of strong directivity effects associated with strike-slip rupture of the earthquake source. Stations WNHS and WEMS also show strong amplitude at ~0.5 second period but in a more E-W direction. Amplification and NE-SW polarization at ~1s period is again observed at deep soil stations and those close to the basin edge.

OVERALL IMPACT ON BUILDINGS IN WELLINGTON

Land in parts of the reclaimed port area typically received up to twice the ground shaking of other locations. Only a few buildings, typically 6 to 12 storeys, were significantly affected. This may have been due to the nature of the shaking (0.4-1 second periods of peak spectral acceleration). Other buildings including unreinforced masonry construction and houses were generally unaffected structurally and most are no worse than before the events.

Most damage related to the inability of building components to accommodate seismic displacements:

- Rigid glazing in older steel framed windows
- Seismic flashings between buildings
- Plasterboard panels in stairwells
- Stairs and ramps

Damage to suspended ceilings and sprinkler pipework was relatively common.

There was some liquefaction observed near Wellington Harbour, and this is touched-on in Van Dissen *et al*. (2013). There was also widespread damage to wine storage tanks in the Marlborough region, as discussed in Morris *et al*. (this issue).

It's worth noting ongoing research focused on Wellington building response. As part of the GeoNet building instrumentation program, there were 6 structures in the Wellington region instrumented with strong motion sensors. These will provide a wealth of data (Uma *et al*. 2011) for detailed analysis of building response during these earthquakes, as well as future ones.

In addition, a group from the University of Auckland, with the help of consulting engineers, installed temporary instruments to monitor building vibrations during the Cook Strait aftershock sequence. This work provided valuable data for structural dynamic research, in particular, for studies into typical damping values for different building types. This work also assisted consultants to refine their modeling approach.

ACKNOWLEDGMENTS

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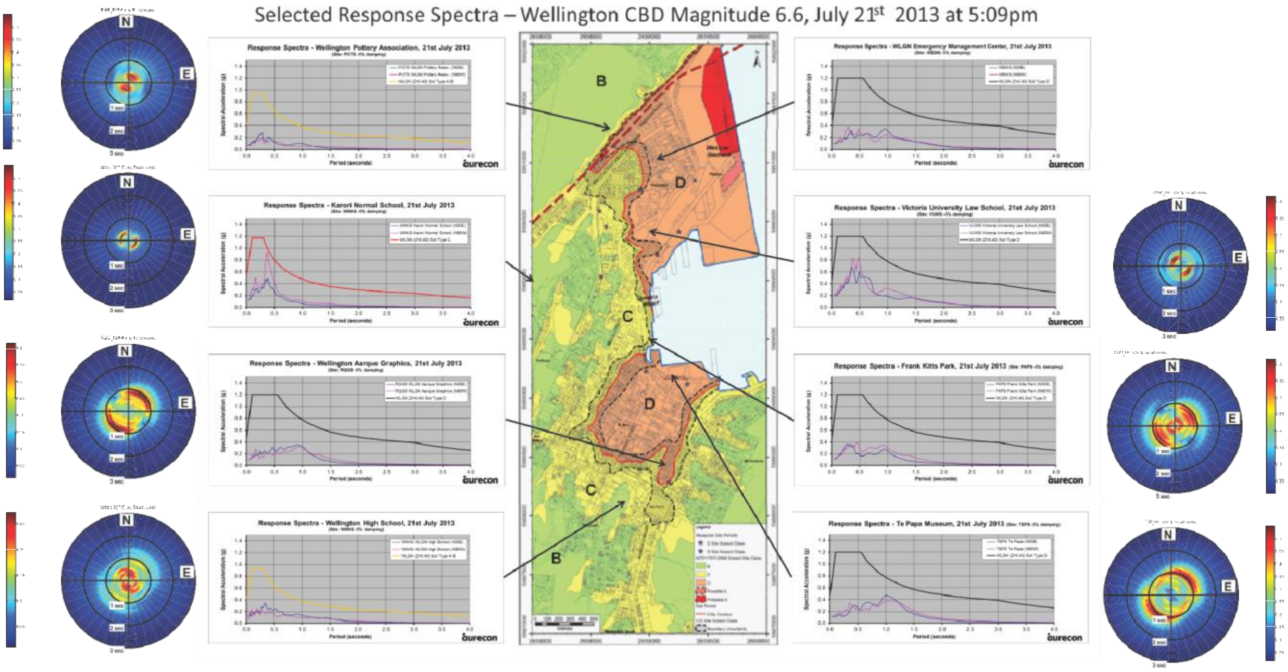


Figure 4: The grey plots are response spectra (5% damping) recorded in central Wellington following the Cook Strait earthquake compared with design levels for respective subsoil site-classes (the response spectra plots are courtesy of T. Holden, and subsoil site classes are from Semmens et al. 2011). The polar plots represent the response spectra (5% damping) for component directions ranging from 0 to 360 degrees. The polar plots are plotted for periods up to 3 seconds; each concentric black circle represents a discrete period value (1, 2 and 3 seconds as per white labels). The polar plots illustrate not only peak periods but also the dominant polarization direction of the response spectra at these peak periods. A broader peak or 'bump' in spectral acceleration at ~1 second period is observed at many Wellington sites, most strongly at those located on deep soil within the basin (TEPS, FKPS, VUWS, WEMS, RQGS), but also at stations near the basin edge (WNHS, POTS). Polar plots indicate a SW-NE polarization of the response spectra at ~1 second period at these stations.

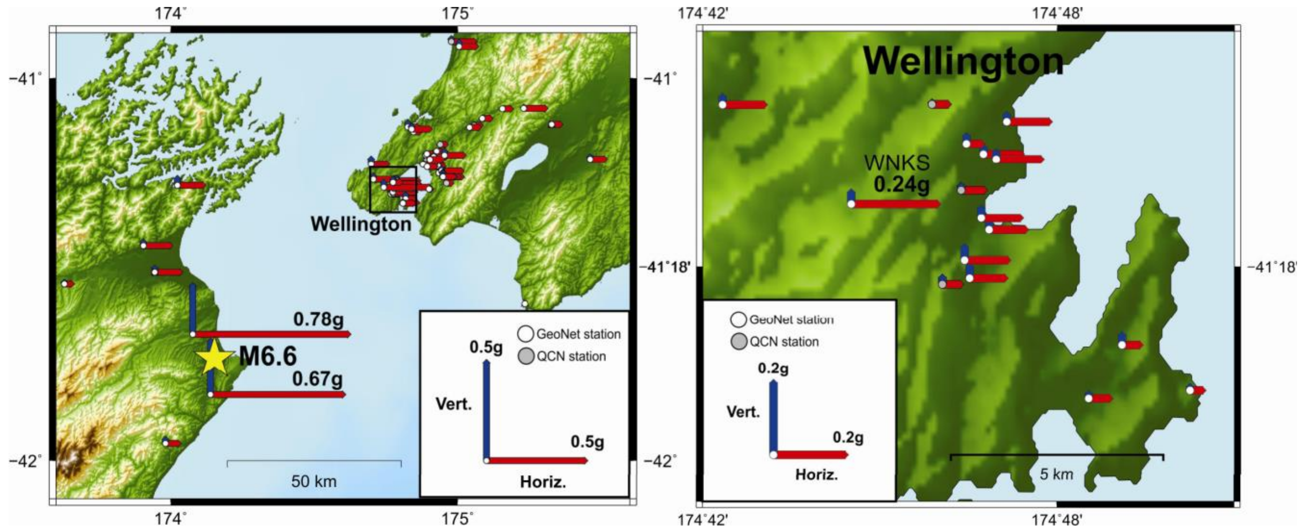


Figure 5: Observed peak ground acceleration (PGA) at GeoNet and temporary QCN stations (see Kaiser et al. (2011) for more detail) during the M_W 6.6 Lake Grassmere earthquake (epicentre shown as yellow star). Location of right figure detailed in left figure, and note the change of scale between the two figures.

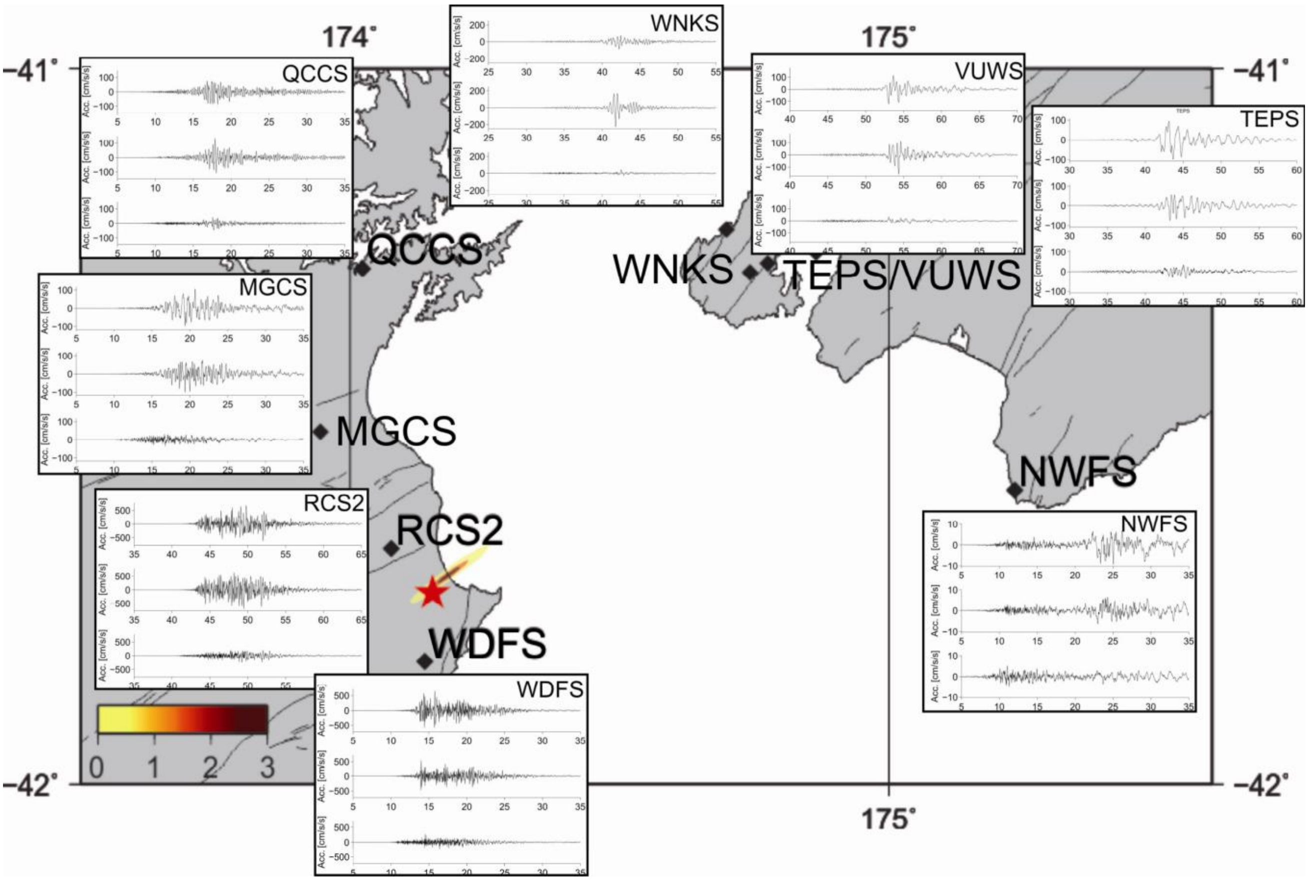


Figure 6: ***Observed ground motions at selected GeoNet stations during the Lake Grassmere earthquake (Contribution from R. Benites, GNS Science). Slip (warm colours; scale in metres) is projected onto the inferred fault plane in map view; for a detailed slip distribution see Figure 7. The pattern of ground motion observations indicate significant directivity effects broadly consistent with southwest-to-northeast strike-slip rupture; i.e. strong S phases are observed in the Wellington region northeast of the rupture, but not at many South Island stations. (Seismograms are displayed from top to bottom in this order: fault parallel, fault normal and vertical components).***

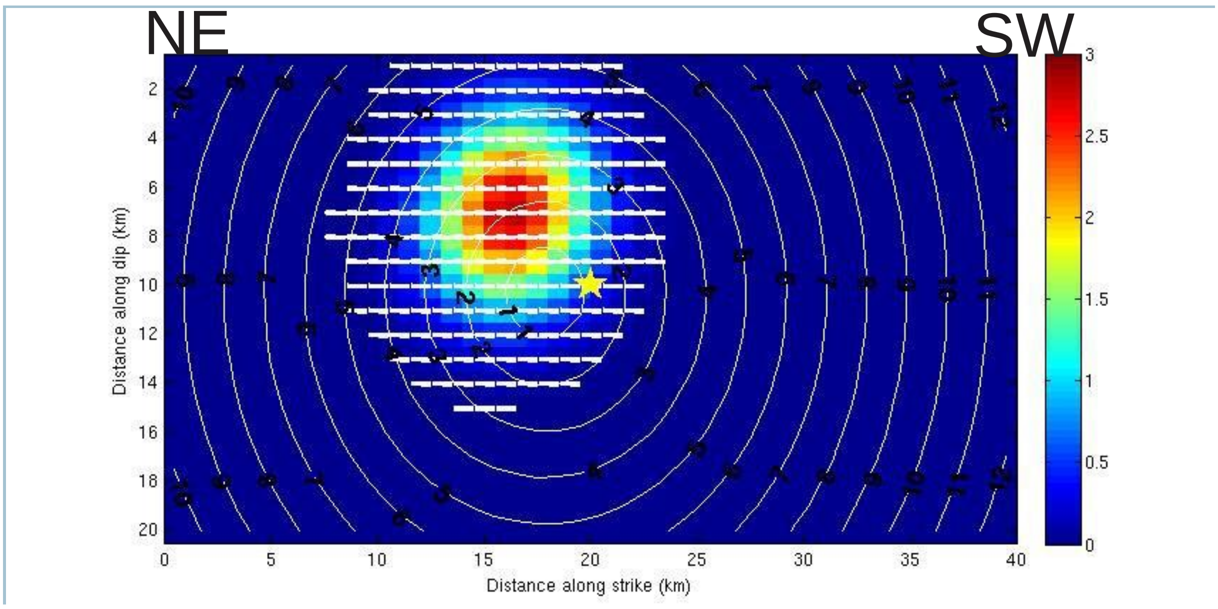
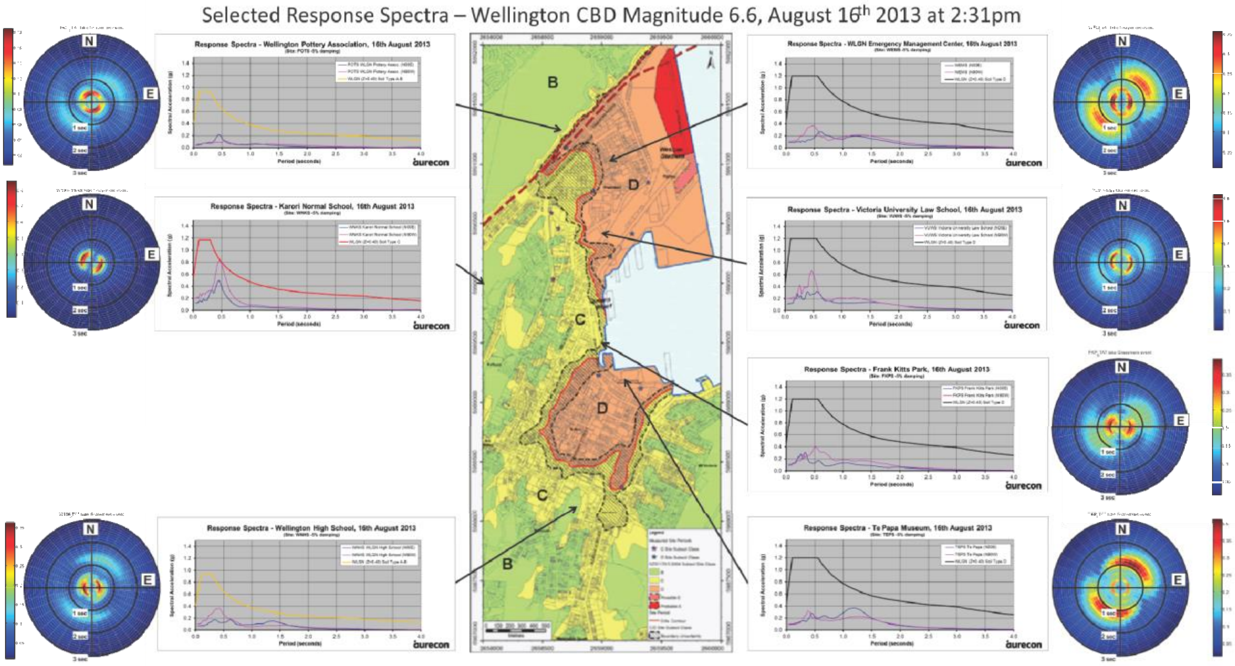


Figure 7: ***Proposed kinematic model (looking from the North) of the Lake Grassmere earthquake, based on static fault parameters (strike 235 and dip 83): the rupture time contours are in white isochrones, the red star is the GeoNet hypocentre location and colours represent slip amplitudes (scale in metres). Max slip 2.8 m at 7.2 km (shallowest slip is 0.25 m at 1 km depth), rake 178 degree, rupture velocity 2.8 km/s. This model suggests a strong directivity effect towards Wellington in a Northwest direction.***



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