2. GEOLOGICAL ASPECTS

Summary

At 4:35 am on September 4th NZ Standard Time (16:35 Sept 3rd UTC) the rupture of a previously unrecognized strike-slip fault beneath the Canterbury Plains of New Zealand's South Island produced a Mw 7.1 earthquake that caused widespread damage throughout the region. Although this earthquake caused much damage to the Canterbury region, it allowed the dynamics and effects of a major strike-slip fault rupture to be documentedin the fortuitous absence of death or major injuries. The low relief and well maintained agricultural landscape of the Canterbury Plains provided an ideal environment to characterize even the most subtle of earthquake-related ground deformation at high resolution. This chapter summarizes the basic geological context and ground rupture characteristics of the earthquake.

Geological context for the Darfield (Canterbury) earthquake

The tectonic plate boundary between the Australian (A) and Pacific (P) Plates passes through the South Island of New Zealand, where subduction of the Hikurangi Plateau to the north transitions into a continent-continent collision zone associated with the collision of the Chatham Rise with continental crust of the Australian Plate (Figure 2.1). The A and P plates converge obliquely at 48–39 mm/yr in New Zealand. The resultant collision zone between these plates is not a line on a map, but rather it is a distributed zone of active faults each with their own capability of generating large earthquakes throughout/around New Zealand. The Marlborough Fault Zone consists of a series of large, 'transpressional' faults that undergo primarily right-lateral displacement with a component of shortening, resulting in mountain uplift. These faults ultimately link to the Alpine Fault, which accommodates ~70-75% of the total relative plate boundary motion between the A-P Plates with a values of 27 ± 5 mm/yr of strike-slip and 5–10mm/yr of dip-slip (see review in Norris and Cooper 2001). The remaining ~30% of A-P plate motion is accommodated by slip on a series of faults throughout the Southern Alps and Canterbury Plains. The Greendale Fault, which was the source of the 2010 Darfield (Canterbury) earthquake, is one of these structures, although it was not recognized prior to this earthquake. Much of the motion is likely taken up on other big faults, such as the Porter's Pass Fault, which has a slip rate of 3-7 mm/yr (3–5 mm/yr; e.g. Cowan et al. 1996; Howard et al. 2005; 7 mm/yr; Wallace et al. 2007). Modeling of GPS-derived velocity fields suggests a strain rate of ~2 mm/yr of WNW oriented permanent contraction for the region east of the Porter's Pass Fault to offshore of Christchurch that hosts the Greendale Fault ("Canterbury Block"; Wallace et al. 2007). There are several structures in this region, both expressed at the surface and 'hidden' beneath the surface, that pose an earthquake hazard to Christchurch (e.g., Hororata Fault, Hororata anticline, Springbank Fault, Bobby’s Creek Fault, Greendale Fault). E-W trending faults are present throughout Canterbury and offshore on the Chatham Rise, and some of these are now 'active' faults (i.e. faults that have had large earthquakes in the last ~10,000 yrs and/or have the potential to generate earthquakes in the modern setting). In a general sense, E-W trending faults like the Greendale Fault tend to be strike-slip dominated faults (e.g., Porter’s Pass Fault; Bobby’s Creek Fault, Ashley Fault) while NE-SW to N-S trending faults tend to be reverse-slip dominated faults with smaller components of strike-slip (e.g., Springfield Fault, Springbank Fault, Hororata Fault). As is clear from this recent earthquake, it is important to obtain more information on the locations of all active faults beneath the Canterbury Plains (via geophysical and mapping investigations) and earthquake histories of all faults (via mapping and paleoseismic analysis) in order to better understand the risk that these structures pose to the Canterbury region (Pettinga et al. 2001).

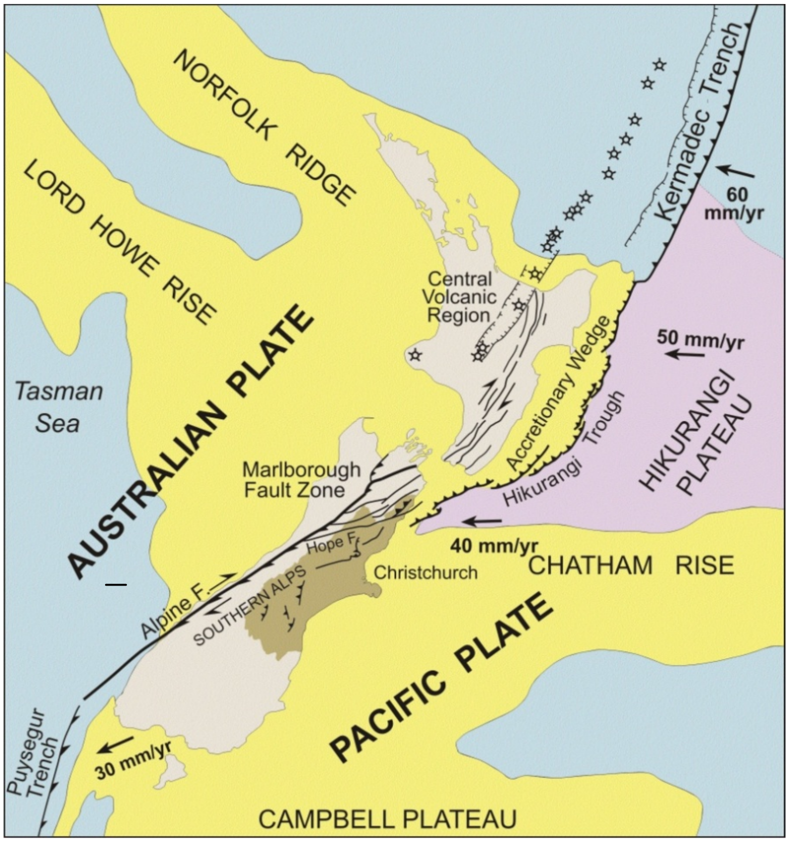

Figure 2.1 A-P plate boundary through New Zealand and convergence rates of P relative to A Plate. (Image courtesy of Jarg Pettinga)

The 4 September 2010 Darfield (Canterbury) earthquake

The epicenter of the earthquake was located approximately 10 km southeast of the town of Darfield (Figure 2.2) with a focal depth of ~10 km. Preliminary USGS and global centroid moment tensor solutions indicated the mainshock was associated with almost pure dextral (right-lateral) strike-slip slip on a subvertical nearly E-W striking fault plane. The event produced a ≥28-km long, dextral strike-slip surface rupture trace, aligned approximately west-east (Figure 2.2). Using data from New Zealand national and strong-motion seismic networks, GNS seismologists have proposed that the rupture process involved a component of reverse faulting at depth. In the month following the mainshock, the region has incurred thousands of aftershocks of $M_L>2$ including eleven aftershocks of $M_L \geq 5.0$. A M_L 5.2 aftershock on 8 September (NZST) located ~7 km southeast of the city center at a depth of ~6 km caused further damage to city infrastructure. The frequency of $M_L>2$ aftershocks has decreased by an order of magnitude since the days immediately following the mainshock although the possibility of $M \geq 5$ earthquakes still remains, as the region adjusts to the crustal deformation associated with the mainshock.

Figure 2.2 Aerial image of the Christchurch area with the surface fault rupture and the epicenter of the Darfield earthquake are denoted. The image is ~117 km across.

Aftershock distributions proximal to the E-W trending part of the Greendale Fault are dominated by ~E-W trending dextral strike-slip mechanisms, as expected from kinematic analysis of the patterns of ground rupture. A NE-trending cloud of aftershocks west of the Greendale Fault, between Hororata and the Rakaia River is dominated by ~NE trending thrust fault mechanisms. A NE-trending cloud of aftershocks north of the Greendale Fault, between Darfield and the Waimakariri River is a mixture of ~NE trending thrust fault and strike-slip fault mechanisms. A NNW-trending swarm of seismicity from ~5 km north of Rolleston south to Lincoln consists of a mixture of NW-trending normal fault mechanisms and (probably) E-W trending dextral strike slip mechanisms. The NE and NW trending belts of seismicity are consistent with field observations of subtle deformation in these localities although these aspects require further research.

Characteristics of the surface fault rupture

The zone of identified surface rupture extends from ~4km WNW of the hamlet of Greendale for about 28 km to an eastern tip ~2 km NW of the town of Rolleston (Figure 2.2). Offsets and fracture patterns reveal up to 4.6 meters of displacement, with an average displacement of ~2.3 m across the entire rupture. Figure 2.3 shows comparisons of the average and maximum fault displacements with global fault data compiled by Wells and Coppersmith (1994). As may be observed from these comparisons, the average and maximum displacements are slightly larger, but very close to, the best fit line of the global fault data. The displacement on the Greendale Fault during the Darfield earthquake was dominated by dextral (right lateral) movement (Figure 2.4). Vertical offsets of up to ~1m occur at constraining or releasing bends. Oblique east-side down slip on the NW-striking western portion of the fault resulted in partial diversion of the Hororata River. The gross morphology of the fault is that of a series of E-W striking, NE-stepping surface traces that in detail consist of ESE-trending Riedel fractures with right-lateral displacements, SE-trending extensional fractures, SSE- to S-trending Riedel' fractures with left-lateral displacements, and NE-striking thrusts and folds. Offsets as small as 1-5 cm were able to be mapped due to the numerous straight features (e.g., roads, fences) crossing the fault. As a consequence, the Greendale Fault surface rupture length (SRL) has been measured to a high level of confidence. However, when the SRL is plotted against Moment Magnitude (M_w), and compared to global fault data (Figure 2.5), the Greendale SRL seems remarkably short for an M_w7.1 earthquake. This is likely because much of the fault rupture occurred beneath the surface without any clear surface topographic expression. An ENE trending, ≥6 km long line of broken fences and roads ~2 km south of Prebbleton may indicate the presence of another fault that ruptured coincident with the Greendale Fault; this hypothesis is currently being tested with further geological mapping and shallow crustal geophysics. The eastern tip of the fault is also creeping slowly, suggesting it is possible that the subsurface extent of the Greendale Fault extends further to the east then the surface rupture. Ongoing research and mapping of deformation throughout the region will provide additional constraints on the spatial pattern of surface rupture.

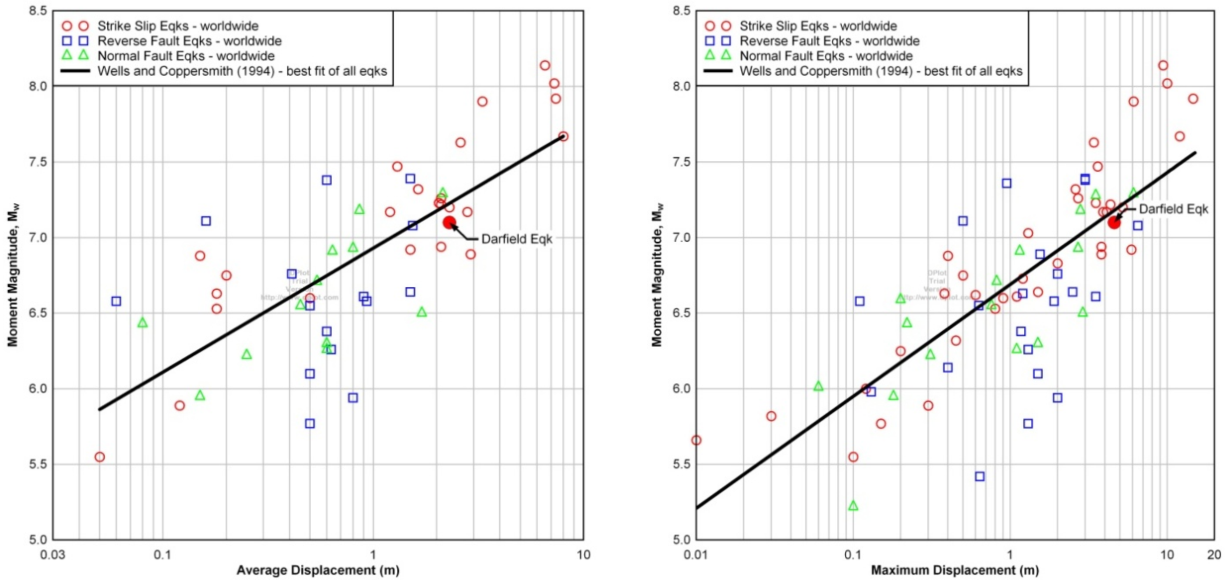

Figure 2.3 Comparisons of average (left) and maximum (right) surface rupture displacements for the Darfield earthquake with global fault data compiled by Wells and Coppersmith (1994) (global fault data courtesy of Don Wells)

Figure 2.4 Photographs of surface fault rupture on the Greendale fault (left photo: http://daveslandslideblog.blogspot.com/2010/09/images-of-darfield-canterbury.html).

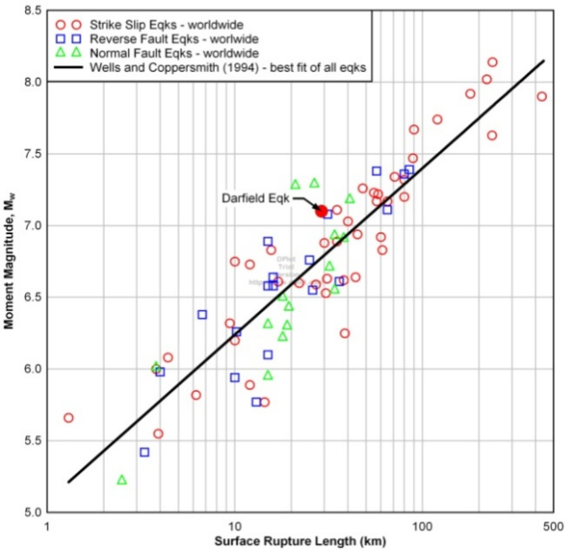

Figure 2.5 Comparison of surface rupture length (SRL) for the Darfield earthquake with global fault data compiled by Wells and Coppersmith (1994) (global fault data courtesy of Don Wells).

History of the Greendale Fault

Given the E-W strike of the Greendale Fault, it is very likely that this fault first formed during crustal extension more than 50 to 60 million years ago, when the shape of New Zealand (aka Zealandia) was much different than it is today. The Greendale Fault ruptured primarily across alluvial plains of the 'Burnham' surface, abandoned by rivers at the end of the Last Glaciation (Forsyth et al. 2008). No evidence of previous faulting had been recognized, either prior to the earthquake or in retrospective examination of pre-earthquake aerial photographs. However, thorough cultivation of the Canterbury Plains following the arrival of Europeans in the mid 1800s has subdued some detail of the original river channel form. Vertical offset along much of the new fault trace was minimal, given the strike-slip dominated movement, and it is probable that previous earthquakes had small vertical-to-lateral displacements that would have evolved with time into isolated small hills that would not be easily recognizable as fault scarps. It is also possible that previous earthquakes did not produce surface rupture, as was the case for the 2010 M_w7.0 Haiti earthquake, which showed no evidence for faulting at the surface. For these reasons, it is important to be cautious when drawing conclusions on the long term earthquake history of the Greendale Fault based on aerial photographs. Future research into 'paleo-liquefaction' features and fault trenching will hopefully yield datasets relevant to understanding the long-term history of this fault. Other, possibly analogous faults (e.g., Bobby's Creek Fault, Ashley Fault) have Holocene earthquake recurrence intervals ranging from 1000-4000 yrs.

Geomorphology of Soil Deposits in the Christchurch Area

The Canterbury Plains, about 160 km long and of varying width, are New Zealand’s largest areas of flat land. They have been formed by the overlapping fans of glacier-fed rivers issuing from the Southern Alps, the mountain range of the South Island. The plains are often described as fertile, but the soils are variable. Most are derived from the greywacke of the mountains or from loess (fine sediment blown from riverbeds). In addition, clay and volcanic rock are present near Christchurch from the Port Hills slopes of Banks Peninsula.

The city of Christchurch is located at the coast of the Canterbury Plains adjacent to an extinct volcanic complex forming Banks Peninsula. Most of the city was mainly swamp, behind beach dune sand, and estuaries and lagoons, which have now been drained (Brown et al., 1995). The two main rivers, Avon and Heathcote, which originate from springs in western Christchurch, meander through the city and act as main drainage system. The Waimakariri River with its catchment in the Southern Alps, regularly flooded Christchurch prior to stopbank construction and river realignment, which began shortly after the city was established in 1850.

Of particular relevance to the liquefaction and lateral spreading that occurred during the Darfield earthquake are the locations of the abandoned/old river channels of the Waimakariri River. The area surrounding Kaiapoi as it exists today is shown in Figure 2.6. The main branch of the Waimakariri River flows from the west to the east, curving northwards as it passes beneath the town of Kaiapoi. A network of levees (stopbanks) has been constructed to constrain the flow of this river along this route. The Kaiapoi River runs through the center of Kaiapoi and is a tributary to the Waimakariri River. However, as discussed below, the Kaiapoi River used to be a branch of the Waimakariri River.

Figure 2.6 Kaiapoi and vicinity, present day. The distance from the left to right edges of the map shown is ~13 km. (Google Inc. 2010)

The area shown in Figure 2.6 is also shown in Figure 2.7, as it existed in 1935. The differences in the river channels from 1935 and the present have been highlighted. The red dashed line represents the current position of the Waimakariri River, showing that there has been little movement between 1935 and today. However, two differences in the locations of the river channels are highlighted in red and green in Figure 2.7. The red zone highlights an old river bed that is south of the Waimakariri River and that runs in a north-easterly direction, connecting to the Waimakariri River. A man-made channel diverts the flow of the Waimakariri River from the old bed. The green shaded region highlights the course of the old north branch of the Waimakariri River that used to flow around the western side of Kaiapoi, joining up with the present day Kaiapoi River in the center of town. Finally, at the mouth of the Waimakariri River, the differences in sand bar characteristics in 1935 and today are highlighted in blue. Today the Waimakariri River empties into the ocean north of where it did in 1935, with sand bars extending from both the north and the south in 1935.

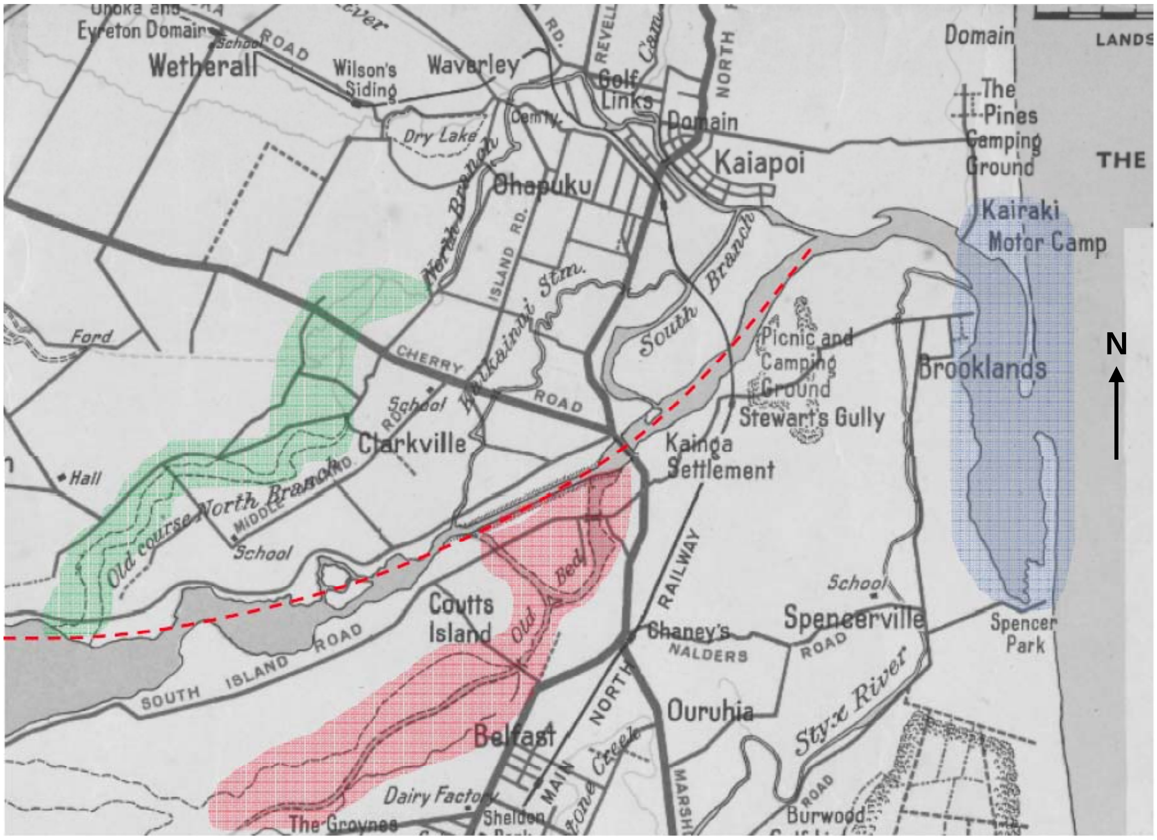

Figure 2.7 Kaiapoi and vicinity, 1935. The distance from the left to right edges of the map shown is ~13 km. (Image from Christchurch City Libraries; Shell NZ, 1935)

Figure 2.8 shows the region circa 1865. To the left of the figure, it can be seen that the Waimakariri River split into two branches, the south and north branches shaded in red and green, respectively. Compare the current position of the Waimakariri River, denoted by the dashed red line, with the location of the two branches in 1865. Most notably, the confluence of the present-day Kaiapoi River and the south branch of the Waimakariri River was much closer to the Kaiapoi town center in 1865. Also, the present day South Kaiapoi is located on what was then known as Kaiapoi Island. Finally, the mouth of the Waimakariri River is again highlighted in blue, with the northerly and southerly projecting sandbars being similar to those shown in Figure 2.7.

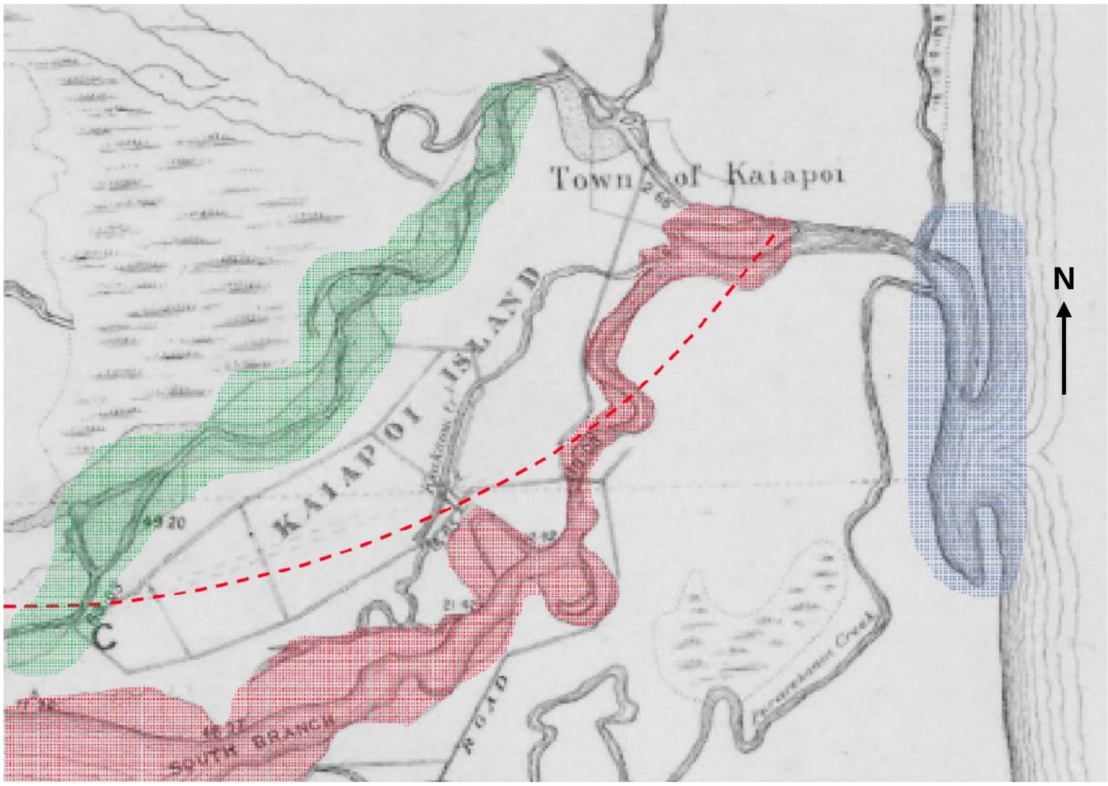

Figure 2.8 Kaiapoi and vicinity, 1865. The distance from the left to right edges of the map shown is ~13 km. (Ward and Reeves, 1865)

The 1865 position of the south branch of the Waimakariri River is superimposed onto the present day map of the region in Figure 2.9. The old channel covers a large area on the eastern side of South Kaiapoi, coming from the south along the present-day railway line. South of the present-day Waimakariri River, the old channel covers a large part of the Coutts Island area on both sides of State Highway 1, extending west across farms and golf courses on the landside of the present day levees. The implications of the location of the old river channel on the observed liquefaction and lateral spreading that occurred during Darfield Earthquake are discussed in subsequent chapters.

Figure 2.9 Present day Kaiapoi with position of 1865 river channel highlighted in red. The distance from the left to right edges of the map shown is ~13 km. (Google Inc. 2010)

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