2. GEOLOGICAL SETTING

2.1. Summary

The moment magnitude M_w7.8 Kaikoura Earthquake occurred on the 14 November 2016 at 12:02 am NZ Standard Time (11:02:56 UTC). The rupture initiated beneath the Waiau Plains in North Canterbury and propagated over 150 km north-eastward progressively stepping over segments of at least twelve faults within the region. The complex sequence involving ruptures on multiple faults resulted in the cumulative M_w7.8 earthquake with a bracketed shaking duration of approximately two minutes. The earthquake was felt throughout much of New Zealand and resulted in widespread damage to land and infrastructure in the northern South Island and lower North Island. Efforts to characterize the distribution of ground deformation and associated rupture traces are on-going due to the remoteness of much of the area and complex nature of the ground surface rupture traces including accommodation of strain on many different tectonic structures. This chapter summarizes the basic geological context of the earthquake and affected regions which are discussed further in this report.

2.2. Geological context for the Kaikoura Earthquake

The South Island of New Zealand straddles the tectonic plate boundary between the Australian and Pacific Plates (Figure 2.1). The plate boundary transitions from oblique continent-to-continent collision between the Pacific plate and the Australian plate across the central South Island, to subduction of the thick oceanic crust of the Hikurangi Plateau beneath the Australian Plate in the NE. Subduction extends northward from Kaikoura in NE South Island along the Hikurangi Trough off the east coast of the North Island (Figure 2.1).

The Australian and Pacific plates converge obliquely at rates of 39-48 mm/yr within New Zealand resulting in a wider zone of collisional deformation marked by a distributed zone of active faulting (Figure 2.1). The Alpine Fault accommodates ~70-75% of the total relative plate boundary motion of the oblique continental collision zone within the central South Island and results in the uplift of the Southern Alps (Figure 2.1) (Norris & Cooper, 2001). The remaining ~30% of plate boundary deformation across South Island is accommodated largely by slip on a series of faults throughout the Southern Alps, eastern foothills, and the adjoining Canterbury Plains, as exemplified by the 2010 Darfield (Canterbury) Earthquake rupture of the Greendale Fault (Cubrinovski et al., 2010; GEER, 2010). In the northern South Island, the Alpine Fault splays into a series of north-east trending transpressional strike-slip faults, comprising the Marlborough Fault Zone (MFZ). The MFZ marks the transition zone of the plate boundary from continental convergence onshore into the Hikurangi subduction zone offshore with the southernmost interface of the subduction zone underlying the MFZ at depths of 20-60 km (Little & Jones, 1998; Reyners & Robertson, 2004). The Kaikoura Earthquake initiated approximately 20 km south of the southern strand of the MFZ and propagated north-eastward, rupturing multiple segments of the major mapped faults within the region, along with several previously unmapped faults.

The MFZ accommodates 70-100% of the oblique plate-boundary convergence in the NE South Island resulting in a complex region of active earth deformation extending over 200 km in width (Figure 2.2). Plate motion is accommodated primarily through the four major NE trending transpressive dextral strike-slip faults spaced approximately 30 km apart, including the Wairau, Awatere, Clarence, and Hope faults.

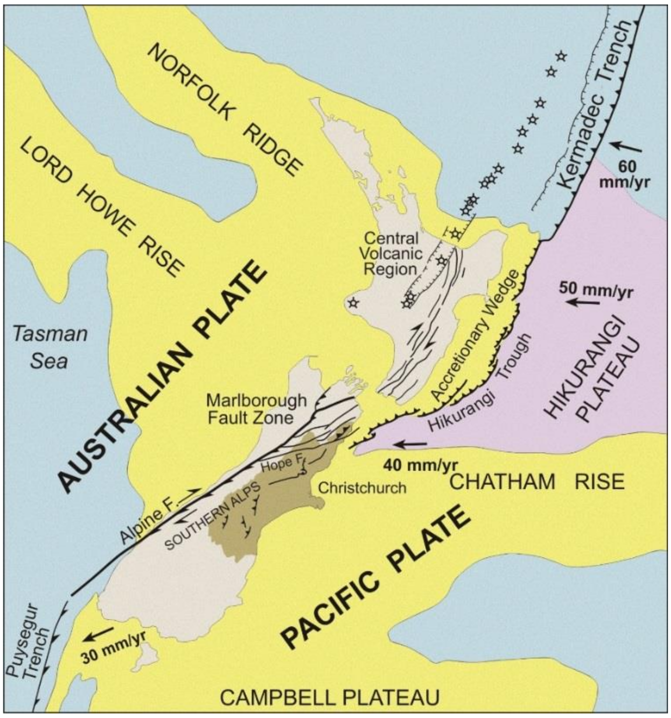

Figure 2.1: The Australian-Pacific plate boundary within New Zealand and associated relative convergence rates (from Pettinga et al. 1998).

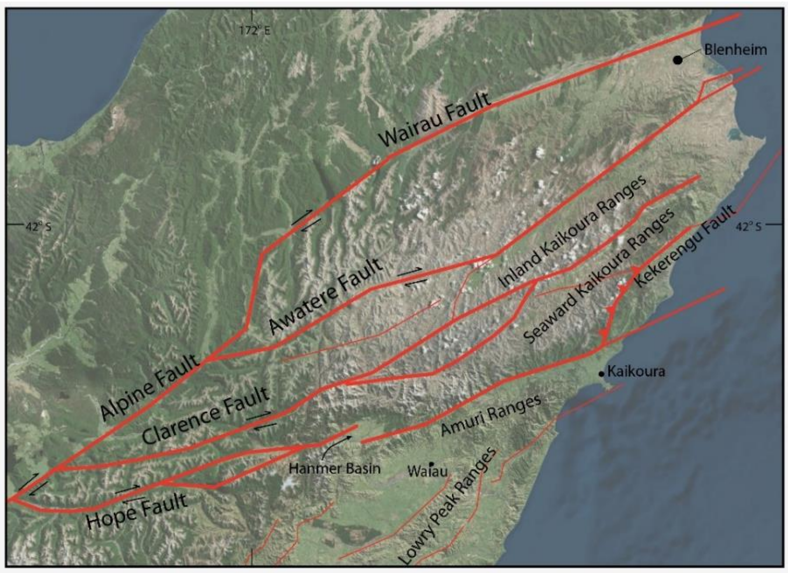

Figure 2.2: Location of active faults and uplifted mountain ranges within the Marlborough Fault Zone (MFZ) in Marlborough and North Canterbury as derived from the New Zealand active faults database (Litchfield et al., 2014).

Slip rates on these faults are well constrained from displaced geomorphic features with Quaternary slip rates on the Wairau, Awatere, and Clarence faults ranging from 4-8 mm/yr (Benson et al., 2001; Nicol & van Dissen, 2002; Zachariasen et al., 2006), while the NE Conway segment of the Hope fault carries approximately 23+/-4 mm/yr of slip (Langridge et al., 2003). Activity within the MFZ has propagated southwards over time as the collisional zone of the Chatham Rise has migrated south (Little & Jones, 1998). A zone of active faulting and folding continues to the south of the Hope Fault and includes the Hundalee Fault and Humps Fault Zone, both of which ruptured during the Kaikoura Earthquake (Figure 2.2) (Pettinga et al. 2001). N-S to NE-SW trending valley and range topography extends south of the MFZ into North Canterbury and is characterised by a set of geologically young and complex faults and related folds associated with the Quaternary widening of the plate boundary zone (Nicol et al., 1995; Pettinga et al. 2001). Smaller mapped and unmapped faults are present throughout the MFZ region and accommodate the remainder of the plate boundary motion.

2.3. The Kaikoura Earthquake

The epicentre of the M_w 7.8 earthquake was located approximately 15 km northeast of the town of Culverden with a focal depth of ~15 km (Figure 2.3). The earthquake rupture initiated on a strand of the Humps Fault Zone beneath north Culverden Basin, and it propagated over 150 km north-eastward, progressively rupturing several mapped and unmapped faults, including the North and South Leader, Hundelee, Jordan Thrust, Papatea and Kekerengu Faults (Figure 2.3). The rupture then transitioned offshore onto the Needles Fault near Ward, and continued for approximately 34 km before the rupture terminated near Cape Campbell off the NE coast of the South Island (Figure 2.3). The rupture of multiple faults within the MFZ during the Kaikoura Earthquake indicates that these structures are most likely connected at depth, possibly in association with the subduction interface. Prior to the Kaikoura Earthquake, the New Zealand Seismic Hazard Model accounted for several rupture scenarios within the MFZ involving ruptures of single faults, as well as combinations of fault ruptures, however, did not account for the complexity or number of faults that ruptured during the Kaikoura Earthquake (Stirling et al., 2012).

The surface rupture traces appear to be discontinuous and segmented with step-overs up to 1 km observed along single faults traces, while jumps in the rupture traces are observed between the ruptured faults. The surface displacement patterns and associated deformation is shown to vary along the length of the rupture traces and between the faults that ruptured (Figure 2.3). Oblique dextral strike-slip displacements of varying magnitudes are typically observed and reported, although localized sinistral displacements are observed (e.g., the Papatea and Stone Jug faults). Maximum horizontal displacements of ~2 m and vertical displacements of up to 2 m were recorded in the epicentral area near Waiau (Figure 2.3), while vertical displacements of up to 4-5 m are reported on the oblique thrust North Leader fault, ~20km NE of Waiau township. Displacements as small as 1-2 centimetres were measured near the epicentre from offset anthropogenic features in farmland including crop-rows, farm tracks, and fence lines. Displacement magnitudes increased as the rupture propagated northward, with up to 10 m of horizontal slip and 7-8 m of vertical displacement recorded on the Kekerengu Fault (Figure 2.3). Offshore seismic surveys conducted by NIWA in the days after the earthquake revealed vertical displacements in the seafloor along the Needles Fault (Figure 2.3).

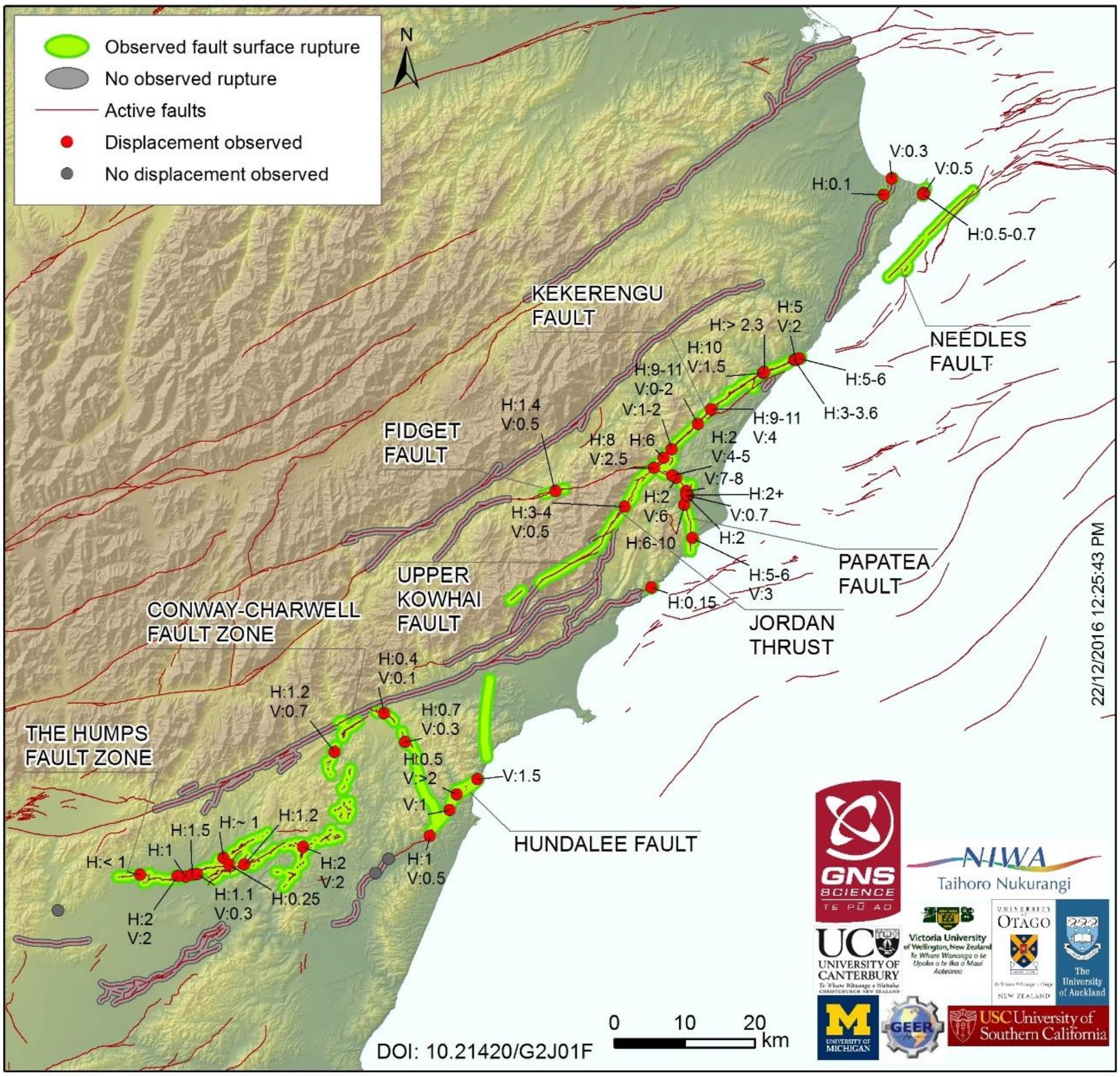

Figure 2.3: Observed and documented fault ruptures as at 22 December 2016 from the 2016 M_W7.8 Kaikoura Earthquake and associated displacements, as measured in the field by scientists from GNS Science, Victoria University of Wellington, University of Canterbury, University of Otago, NIWA, and GEER, among others.

Coastal uplift is observed in the area north of where the Hundalee Fault intersects the coast, and appears broadly controlled by the locations of surface ruptures at the coast (Figure 2.3). Approximately 1 m of coastal uplift is observed proximal to the Hundalee Fault and at the Kaikoura Peninsula (Figure 2.3). The maximum observed coastal uplift occurs where two strands of the Papatea Fault intersect the coast, resulting in the intervening block between the two strands being uplifted by up to ~6 m. Coastal uplift of approximately 2 m continues to the north to the where rupture transitioned offshore onto the Needles Fault (Figure 2.3).

The distribution of aftershocks from the Kaikoura Earthquake generally occur throughout a broad region trending parallel to the rupture traces between North Canterbury and Cook Strait (Figure 2.4). A high proportion of the initial aftershock distribution was concentrated at the northernmost terminus of the surface rupture near Cape Campbell and proximal to the Wellington region in the lower North Island (Figure 2.4). In the two months following the main shock, the region experienced 53 aftershocks of M5-5.9 and four of M6-6.9, which is below that expected for a M_w7.8 earthquake.

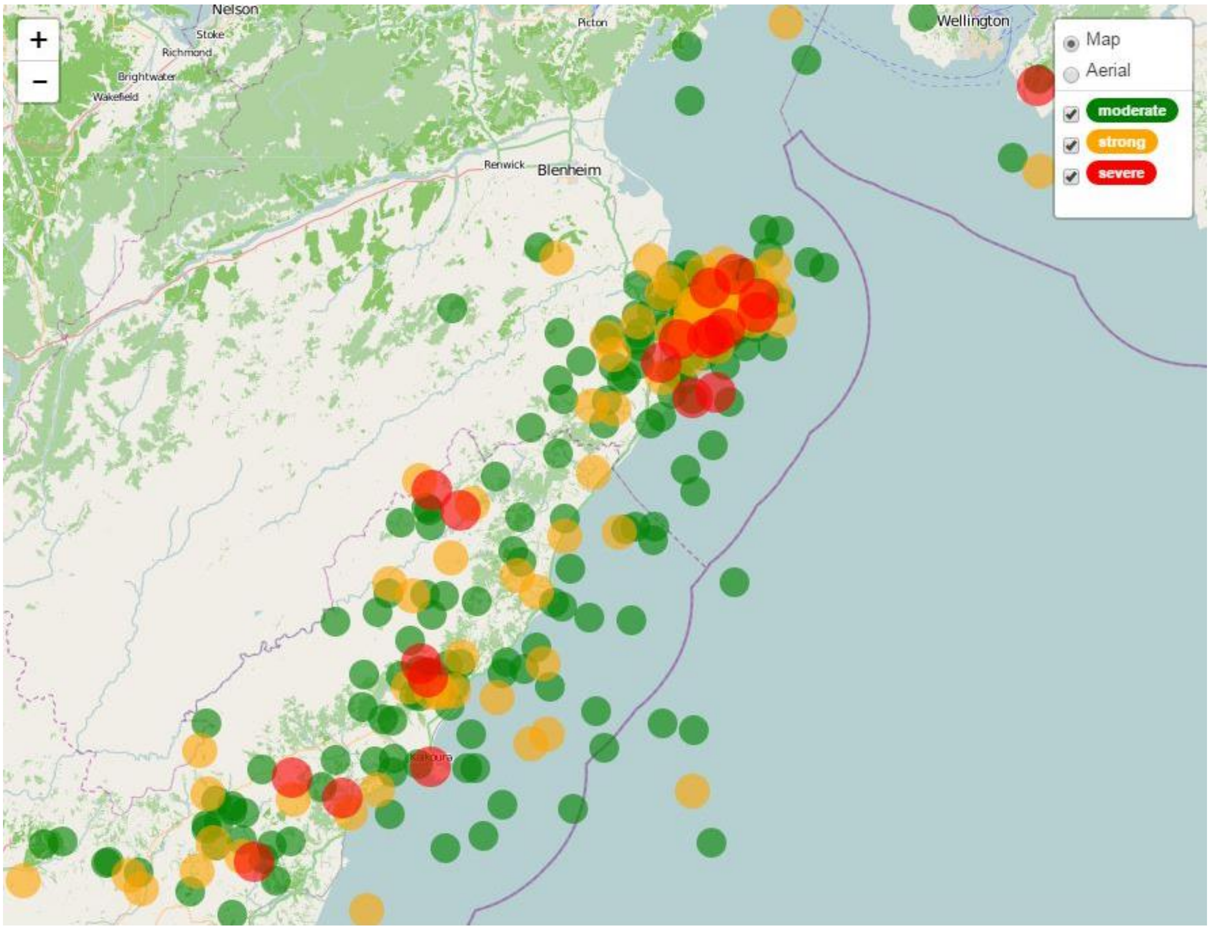

Figure 2.4: Map of aftershock locations in the 24 hours following the M_w7.8 Kaikoura Earthquake as compiled by GeoNET.

2.4. Historic and Pre-historic seismicity within the Marlborough Fault Zone

The MFZ is one of the most tectonically active regions of New Zealand with many shallow earthquakes recorded in the region since initial European settlement and subsequent instrumental monitoring began (Figure 2.5). Two large earthquakes with magnitudes greater than 7.0, and six shallow earthquakes with magnitudes 6.0-6.9 have been recorded in the MFZ post-settlement in ~1840, and prior to the 2016 Kaikoura Earthquake (Grapes et al., 1998). The 1848 ~M7.5 Marlborough Earthquake ruptured approximately 100-110 km of the Awatere Fault extending inland from the coast. Mean dextral co-seismic displacements of 5.3

+/- 1.6 m were derived for this event from later studies by Grapes et al. (1998) and Mason & Little (2006). The earthquake caused extensive regional shaking and damage to buildings, with shaking intensities of MM9-10 inferred in the Wairau and Awatere valleys. Liquefaction was reported close to rivers within the Wairau, Awatere, and Clarence valleys (Grapes et al., 1998). Three deaths were reported within Wellington city (Grapes et al. 1998). Paleo-seismic studies provide evidence for 9-10 surface-rupturing earthquakes on the eastern section of the Awatere Fault between 1848 and 8330-8610 years before present (BP). A mean recurrence interval of 820-920 years has been derived for the fault, however, intervals between individual events are non-uniform (Mason et al. 2006).

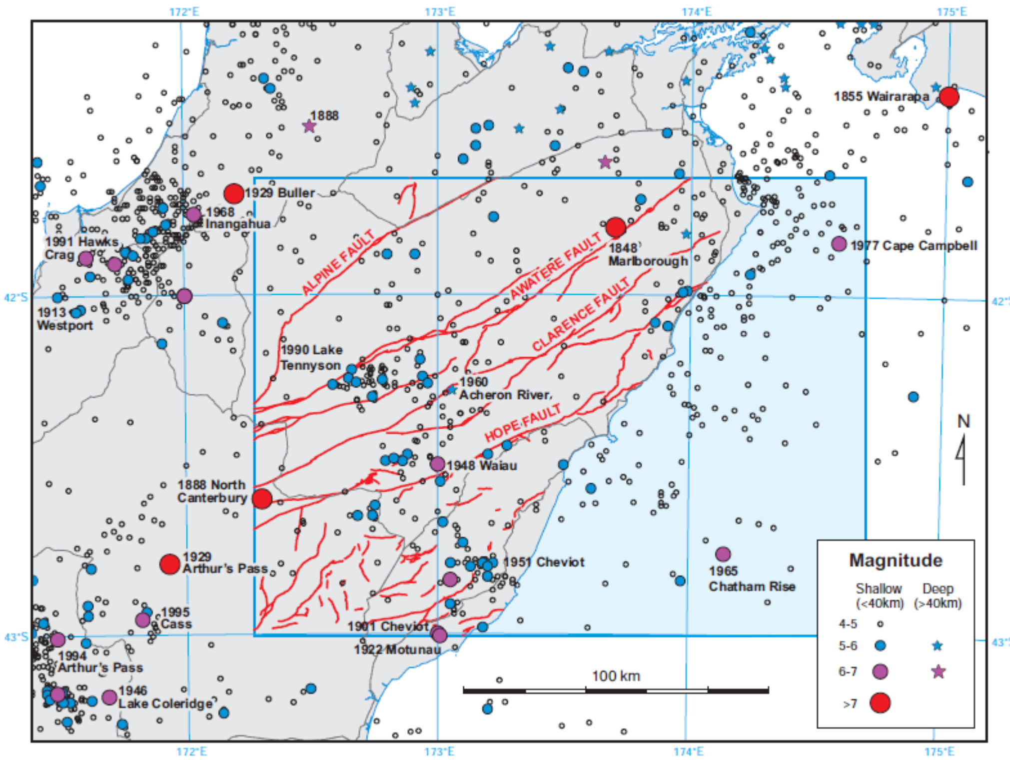

Figure 2.5: Historic earthquakes within the northern South Island of New Zealand (Rattenbury et al., 2006).

The 1888 the M7.0–7.3 North Canterbury Earthquake ruptured a 30 ± 5 km segment of the Hope Fault to the west of Hanmer Springs. Maximum dextral displacements of up to 2.6 m were recorded along the rupture from offset features such as farm fences (Cowan, 1991). The earthquake resulted in a narrow zone of extensive building damage running parallel to the rupture trace, and caused widespread contents damage within the central South Island (Cowan, 1991).

Other damaging earthquakes within the MFZ include the 1901 M6.9 Cheviot Earthquake, and the 1922 M6.4 Motunau Earthquake, both of which caused widespread damage within northern Canterbury (Downes & Yetton, 1995). The 1948 M6.4 Waiau Earthquake also caused minor structural damage in Hanmer and Waiau (Downes & Yetton, 1995). More recently the 2013 M_w6.5 Cook Strait Earthquake, centred 25 kilometres east of Seddon, and the M_w6.6 Lake Grassmere Earthquake, located 30 kilometres SE of Blenheim, caused moderate damage to land and infrastructure near the source region, including triggering liquefaction within the township of Blenheim (Morris et al., 2013).

2.5. Geologic setting and geomorphology of the Marlborough Fault Zone

The geomorphology of the Marlborough region is dominated by NE trending mountain ranges associated with transpressional uplift along the major dextral strike-slip Wairau, Awatere, Clarence and Hope faults of the Marlborough Fault Zone (MFZ) (Figure 2.2). The faults have controlled the formation of long straight NE trending valleys adjoining the range-front location of the active faults, with corresponding rivers approximately aligned with the active fault traces (Figure 2.2). The river courses have been strongly influenced by movements on the corresponding fault segments and associated uplift (Figure 2.2). The mountain ranges generally comprise indurated sandstone and argillite assigned to the Torlesse greywacke basement sequence with local igneous intrusions. Remnants of the Cretaceous-Pliocene covering sequence are preserved in fault-angle depressions on the south-eastern sides of the faults within the major valleys (Rattenbury et al., 2006). Landforms within the valleys reflect alternating glaciations and inter-glacial cycles throughout the Pleistocene with many glaciated landforms offset and deformed by activity and uplift along the faults within the valleys.

The ~220 km long Hope Fault is segmented into three strands as it traverses across South Island and is topographically defined by alignment of major valleys coincident with these major fault splays. At the eastern tip of the central Hope River segment a 7 km wide releasing bend/step-over between this segment and the SE Conway segment (Figure 2.2) has resulted in the formation of the Hanmer pull-apart basin which extends approximately 15 km length (Wood et al., 1994). The North Canterbury region to the south of Hope Fault is comprised of NE-SW to N-S trending ranges, such as the Lowry Peak Ranges, which are significantly lower in altitude to those in the MFZ to the north, and are separated by thrust fault controlled valleys and depressions such as Culverden and Cheviot basins (Figure 2.2) (Nicol et al., 1995; Pettinga et al. 2001). The Culverden and Cheviot basins are partly rimmed by Cretaceous-Miocene sedimentary rocks including Paleogene limestones, and are infilled with Plio-Pleistocene sediments eroded from the surrounding ranges along with Torlesse greywacke-derived sandstone from the exposed and eroding cores of the local thrust propagated anticlinal folds as well as the more distal source regions of the Southern Alps. The fold and thrust driven valley and range topography is transected by the Waiau and Hurunui Rivers which flow eastwards from their upper catchments in the ranges of the Southern Alps. Several antecedent gorges are present along the Waiau and Hurunui Rivers reflecting active and continuing uplift and deformation along the mountain ranges of northern Canterbury.

The rapid and continuing uplift of the mountain ranges within the MFZ, and consequent erosion, provided sediment that infilled the valley floors and intervening basins. Much of the

Quaternary fill within the valleys originated as glacial outwash deposits. Sediments have subsequently been re-worked by the rivers within the valleys. Flights of aggradational terraces comprising gravel with sand and silt lenses are present above the active river floodplains; older terraces are preserved at progressively higher elevations above valley floors. The terrace surfaces are commonly tilted and warped as a result of uplift and fault-driven deformation along the mountain range-fronts. Floodplain deposits in the valleys typically comprise gravel with sand and silt lenses, average clast size and sediment grading decreases towards the coast and with increasing distance from the source. Compositions generally comprise basement Torlesse derived sandstone that outcrops within the mountain ranges. Alluvial fan and scree deposits are widespread along the flanks of mountain ranges and often merge into the aggradation surfaces.

Tectonic activity along the faults within the MFZ has uplifted much of the coastline between North Canterbury and the Kekerengu fault (Figure 2.2). Steep slopes and sea cliffs are present along much of the coastline and are comprised of Torlesse greywacke sandstone, and Paleogene limestones capped by flights of uplifted marine terraces (Rattenbury et al., 2006). The peninsula at Kaikoura comprises uplifted flights of marine terraces underlain by of Late Cretaceous-Paleogene limestone and siltstones as well as upper Tertiary siltstones, and reflects continued uplift of the region throughout the Quaternary (Rattenbury et al., 2006). Poorly preserved and tilted raised shorelines comprising marine sand and gravel are present as narrow benches and terraces along the flanks of the coastal ranges and reflect tectonic uplift rather than actual interglacial sea levels. The coastline north of the Kekerengu Fault generally exhibits low-profile beaches comprised of sand and gravel and commonly fringed by sand dunes. At the mouths of the Waiau and Awatere valleys successions of paleo-dunes indicate coastline progradation and marine regression following the 6,500 year before present sea-level highstand. Offshore, the seafloor morphology is dominated by the continental shelf, the continental slope, the Hikurangi Trough, and the Chatham Rise.

The interface of floodplain alluvium and coastal marine deposits at the mouths of the Wairau and Awatere rivers has resulted in sediments that display significant spatial variability. Swamp deposits are observed in the inter-dune hollows between the paleo-dune ridges present between the Blenheim township and the coast, and reflect water pooling in these areas following flood-events. Active and paleo-channels are present in the area surrounding Blenheim and reflect the migration of the Wairau River and associated tributary streams across the alluvial plains. The distribution of liquefaction and associated lateral spreading proximal to Blenheim appears to be strongly influenced by the position of the present and paleo-streams along with the inter-dune swamp deposits.

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