PATA
DAYS

ONE-DAY FIELDTRIP

Northern Fault Ruptures and Landscape Impacts of the 2016 Kaikōura Earthquake

13TH NOVEMBER 2017

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Cover image: Measuring offsets along the Kekerengu Fault as it crosses farmland near the coast following the 2016 Kaikōura Earthquake.
Photo credit:
Julian Thomson

BIBLIOGRAPHIC REFERENCE

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HEALTH AND SAFETY

PLEASE READ!

There are certain inherent hazards in working along roads and on farms. Participants must heed and observe the warnings and time limitations imposed at certain stops by the trip leaders. Caution must also be exercised when crossing public roads, standing on the road reserve, or farm track locations where vehicles or machinery may be in use.

Participants should carry any personal medications, including those for allergic reactions (e.g. insect stings, pollen, food allergies).

During this fieldtrip we will be stopping near roads and on farm tracks. Hi-visibility vests will be provided and are to be worn at all stops. Please exit on the verge/left side of your vehicle if safe to do so. Do not stand on the road and beware of road traffic AT ALL TIMES.

Leaders will give site specific briefings as we arrive at the stops, please listen carefully and heed all warnings.

CONSIDERATE FIELD TRIPPING

We are privileged to be allowed access onto private property for most stops on this field trip. Residents of the Kaikōura and Marlborough districts are still very much in recovery mode from the earthquake and for many, the earthquake impacts on livelihoods and property have been severe. We would appreciate all field trip participants having consideration and respect for the residents of the area and the land. Please do not leave rubbish or behave carelessly with private property. You are most welcome to take photos and post images on social media but please show sensitivity in your messages and do not publicly share property addresses.

NORTHERN FAULT RUPTURES AND LANDSCAPE IMPACTS OF THE 2016 KAIKŌURA EARTHQUAKE

TRIP INTRODUCTION

We leave on the first morning of PATA Days to visit surface ruptures, damage and coastal uplift sites along the “northern” set of the 2016 Kaikōura earthquake ruptures (Fig. 0.1, 0.2). The route takes us from the southern part of the Hikurangi margin and into the heart of the Marlborough Fault System. Blenheim is located near the Wairau Fault which marks the northern edge of the Marlborough Fault System (MFS). On the journey out of Blenheim on the left are the Wairau Lagoons. The Wairau Lagoons are the field site of the subduction earthquake research where evidence of two past subduction earthquakes at 470-550 and 800-880 yrs BP is recorded in the salt marsh sediment record (Clark et al. 2015). Bordering the southern edge of the lagoon is the Vernon fault which has a slip rate of 0.8–4.9 mm/yr and last ruptured at 3.3 ± 0.5 ka (Bartholomew et al. 2014). As we come down into the Awatere Valley we cross the surface trace of the Awatere Fault (Fig. 0.2). The eastern segment of the Awatere Fault ruptured in a Mw ~7.5 earthquake on October 16,1848 (Grapes et al., 1998). Where the fault crosses State Highway 1 (SH1), c. 1.6 km SE of Dashwood Pass there would have been close to 5 m of right-lateral slip (Mason et al. 2006).

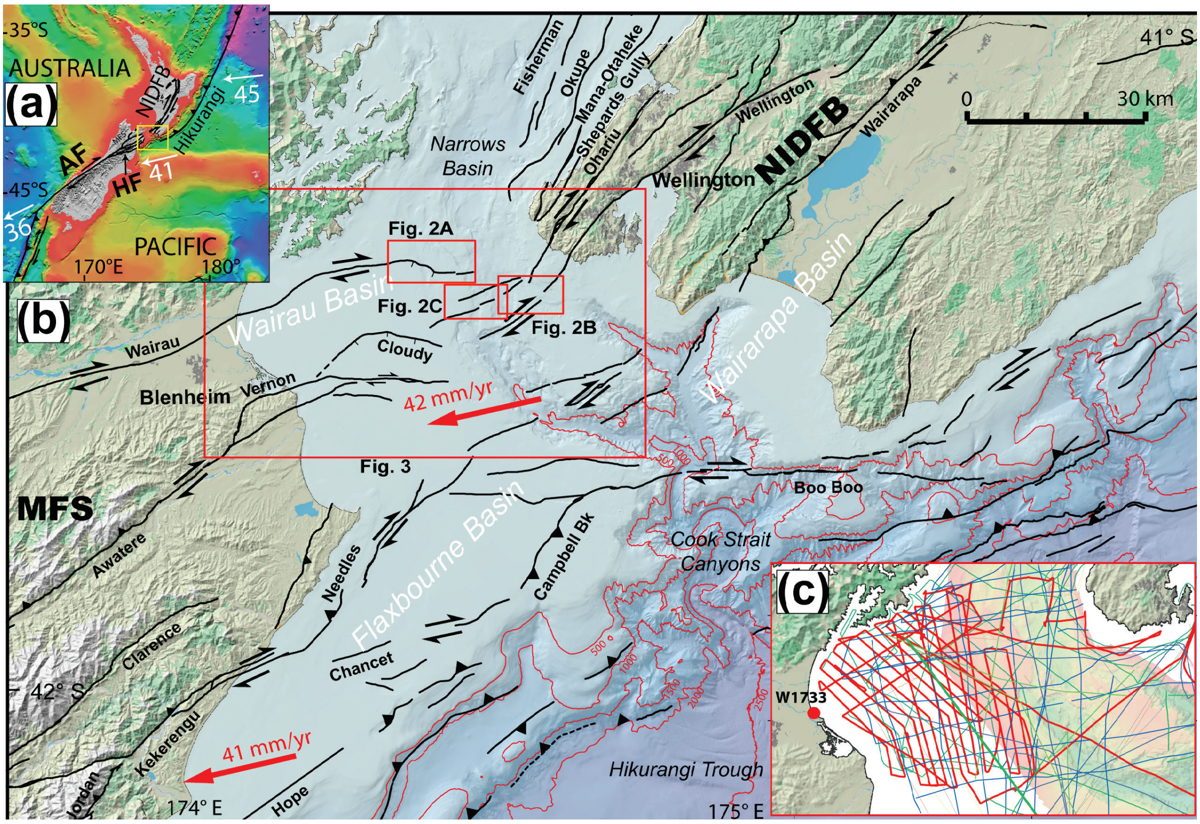


Figure 0.1. Active faults of the southern Hikurangi margin, figure from Pondard and Barnes (2010). (a) Tectonic position of the Cook Strait region (yellow box) within the obliquely convergent Pacific - Australian plate boundary zone. White arrows are Pacific - Australian relative plate motion vectors with velocities in mm/yr. Abbreviations are as follows: AF, Alpine Fault; HF, Hope Fault; Hikurangi, Hikurangi subduction zone. (b) Enlargement of the Cook Strait region, showing active faults (black labels) and bathymetry (500 m contours). Abbreviations are as follows: NIDFB, North Island Dextral Fault Belt; MFS, Marlborough Fault System. (c) Coverage of seismic reflection profiles and extent of SIMRAD EM300 multibeam bathymetric data (colored image).

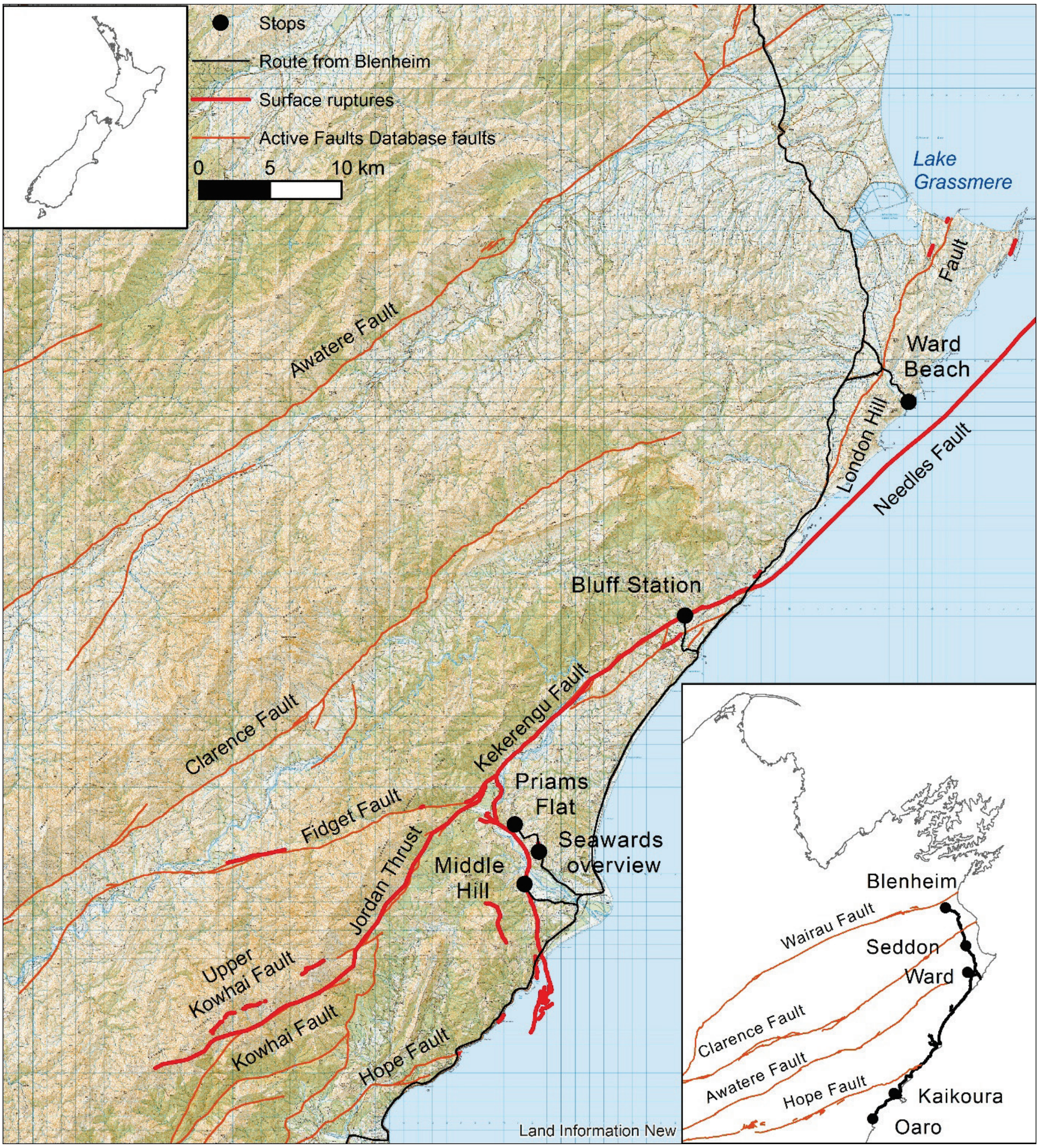


Figure 0.2. Route for the field trip (south from the Awatere Fault/Seddon area). State Highway 1 and other access roads shown in black. Field trip stops shown with black dots. The southern three stops focus on the Papatea Fault and Clarence valley. Inset shows the NE South Island, Blenheim, Kaikōura, other locations mentioned in the text and the Marlborough Faults.

The towns of Seddon and Ward were hit hard by the 2016 Kaikōura earthquake and there has been a particularly rich aftershock sequence at the northern end of the 2016 ruptures (Kaiser et al., 2017). These towns were also badly affected by two moderately large earthquakes that comprise the Cook Strait earthquakes in 2013. The two largest events in this sequence were the Mw 6.5, 21 July Seddon and Mw 6.5, 16 August Lake Grassmere earthquakes (Hamling et al., 2014).

From Seddon, we continue south over Tertiary hills to Lake Grassmere, which is a basin marginal to Cook Strait. One of its claims to fame is that New Zealand's salt supplies are harvested here through evaporative drying. The Lake Grassmere basin is associated with the Ward Syncline and sits to the west of the active London Hill Fault (Langridge et al., 2016).

The order of the stops will differ depending on which bus you are in. We intend to take you all to each of the stops, but due to road conditions and pressure on farm sites, it is best to split into three groups. We have specific expert leaders for each area who will lead discussions. The stops are listed below from north to south:

STOP 1

Ward Beach – Leaders: Kelvin Berryman, Nicola Litchfield, Jamie Howarth. Uplifted coastline and rock platforms. Discussion of co-seismic coastal deformation and the evidence at Ward Beach of past earthquakes.

STOP 2

Kekerengu Fault – Bluff Station and Kekerengu River. Leaders: Russ Van Dissen, Tim Little. Multi-metre Kekerengu Fault rupture.

STOP 3

Seawards overview and Priam’s Flat. Leaders: Rob Langridge, Will Ries. A vantage point on Clarence Valley Rd where we can discuss the Jordan Thrust and Seaward Kaikōura Range. Papatea Fault; surface ruptures on the northern side of the Clarence River valley

STOP 4

Middle Hill Station. Leaders: Kate Clark, Pilar Villamor. Papatea Fault; surface ruptures on the southern side of the Clarence River valley

TOILET STOPS WILL BE AT A PREMIUM ALL DAY. MAKE SURE YOU USE THE FACILITIES WHEN OFFERED.

STOP 1: WARD BEACH

(Leaders: Kelvin Berryman, Nicola Litchfield, Jamie Howarth)

Ward Beach is an excellent location to observe the impacts of coastal uplift that occurred in the 2016 Kaikōura earthquake. Coastal deformation was recorded along 110 km of coastline from Oaro in the south, up to Lake Grassmere (Fig. 1.1). We measured coastal deformation using airborne LiDAR differencing, field surveying and satellite geodesy, and our compilation of coastal deformation measurements showed highly variable vertical displacements, ranging from -2.5 to 6.5 m (Clark et al., 2017). Sharp changes in coastal deformation are recorded at the surface ruptures of the Hundalee, Papatea and Kekerengu faults, while lower amplitude variability in coastal uplift reflects distributed deformation near the major fault surface ruptures, minor fault surface ruptures and slip on nearshore faults subparallel to the coastline (Fig. 1.1).

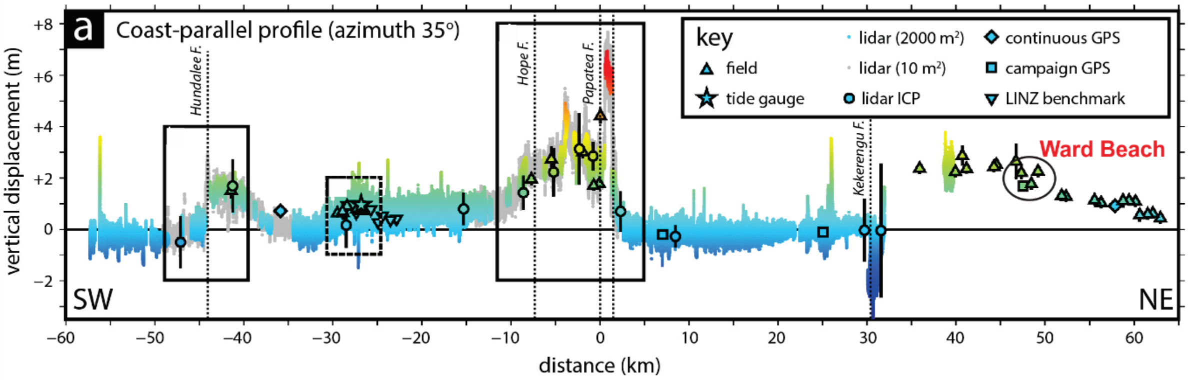


Figure 1.1. Field, LiDAR, and geodetic measurements of coseismic vertical deformation projected onto a straight line of azimuth 35o that roughly parallels the Kaikōura District coastline, see Clark et al. 2017 for more information.

Ward Beach was uplifted by ~2.2 – 2.6 m in the 2016 Kaikōura earthquake. Field teams visited the site within about 5 days of the earthquake and surveyed the amount of uplift using displaced subtidal biota. Working with marine ecologists, we established that the most accurate and reliable biological indicator of former tide levels was the upper limit of bull kelp (*Durvillaea antarctica*) and the associated band of coralline algae on shorelines experiencing high wave energy, whereas the upper limit of *Carpophyllum maschalocarpum* and associated coralline algae was used in areas of lower wave energy (Fig. 1.2). At Ward Beach, you can also observe the uplifted beach berms (Fig. 1.3) and the abandoned estuary (Fig. 1.4).

Uplift of the coastline around Cape Campbell has had a major impact on the local community. Ward Beach was a hub for several local crayfish and paua commercial operations, and the coastline was used by recreational fisherpeople. The paua fishery has been closed since the earthquake while monitoring of the paua stocks is undertaken. Crayfishing operations have re-opened since the earthquake but the uplift of the reefs necessitated major changes to the boat launching areas. In addition, there is tension in the community about the post-earthquake accessibility around the coastline. With the coastal uplift parts of the coastline around Cape Campbell that were formerly difficult to access (e.g. only at extreme low tides) have now become easier to access enabling more recreational users around the coast.

Figure 1.2. Examples of displaced intertidal and subtidal biota; the sharp line delineating the upper limit of bull kelp (*Durvillaea antarctica*) and the associated band of coralline algae is obvious at these locations. (A) Delia chills out by an uplifted rock outcrop ~6 km southwest of Ward Beach, where uplift was ~2.3 m. (B) Location of maximum coastal uplift (~ 5m) at Waipapa Bay, between two strands of the Papatea Fault.

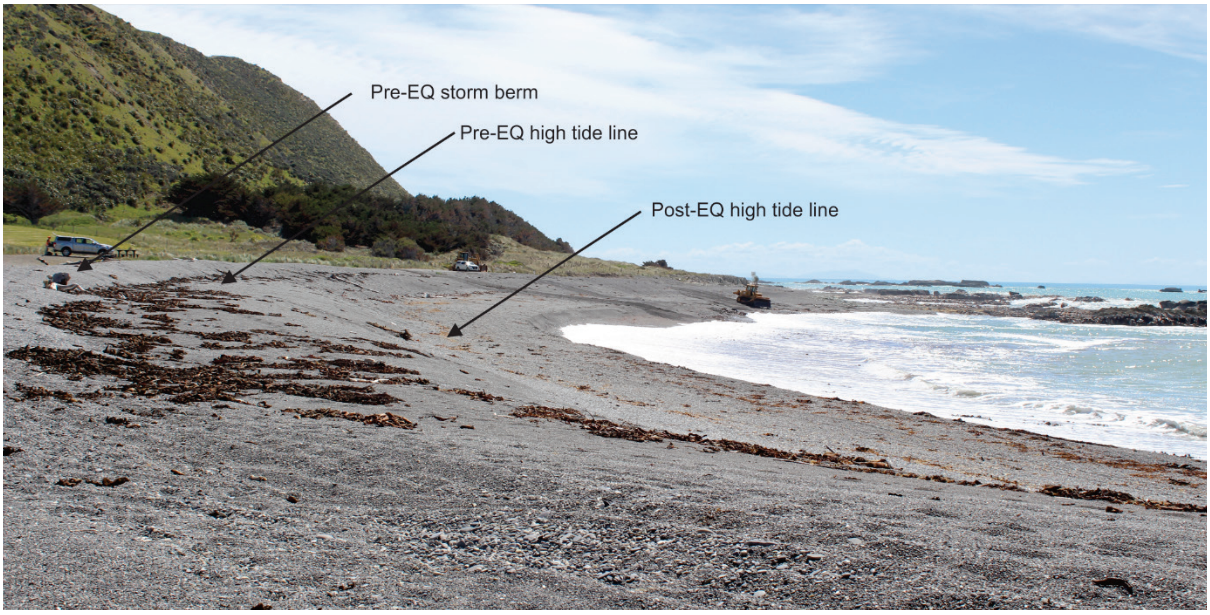


Figure 1.3. Ward Beach – 5 days post-EQ. The mixed gravel-sand beach at Ward is very steep and develops well-defined storm berms. The pre- and post-earthquake storm berms can be observed on Ward Beach.

Figure 1.4. Uplifted estuary at Ward Beach. There is no longer any intertidal zone at this river mouth and the Flaxbourne River is incising through the former estuary bed and gravel beach deposits.

Uplift of the stretch of coastline from the Kekerengu Fault up to Cape Campbell is largely driven by the offshore Needles Fault (Fig. 1.5). Rupture of offshore faults, including the Needles fault (Fig. 0.2), was mapped by NIWA on two post-earthquake marine voyages using multibeam systems. The Needles fault shows a clear surface traces on the seafloor and can be pinpointed as being co-seismic with the 2016 earthquake due to the presence of scarps in the shallow water mobile sediment zone (Fig. 1.6). North of the Kekerengu fault, and inboard of the Needles fault, there was coastal uplift on the order of 2 – 3 m. From a peak of 2.9 m near the Waima River, there is a north-eastward decrease in coastal uplift to 0.4 m at Cape Campbell (with a 0.5 m step across the Lighthouse fault, 2.5 km south of Cape Campbell).

This north-eastward decrease in coastal deformation largely mimics the scarp heights on the fresh rupture trace of the submarine Needles fault and is a function of both diminishing slip on the Needles fault and increasing distance between the coastline and the Needles fault (Fig. 1.5). Evidence of previous Holocene coastal uplift can be seen from the geomorphology around Ward Beach (Fig. 1.8). Fluvial terraces that grade to Holocene marine terraces line the Flaxbourne River Valley and 2 – 3 marine terraces have been mapped along the coastline north and south of Ward Beach. Small remnants of Pleistocene marine terraces north of Ward Beach also attest to long-term tectonic uplift (Ota et al. 1995).

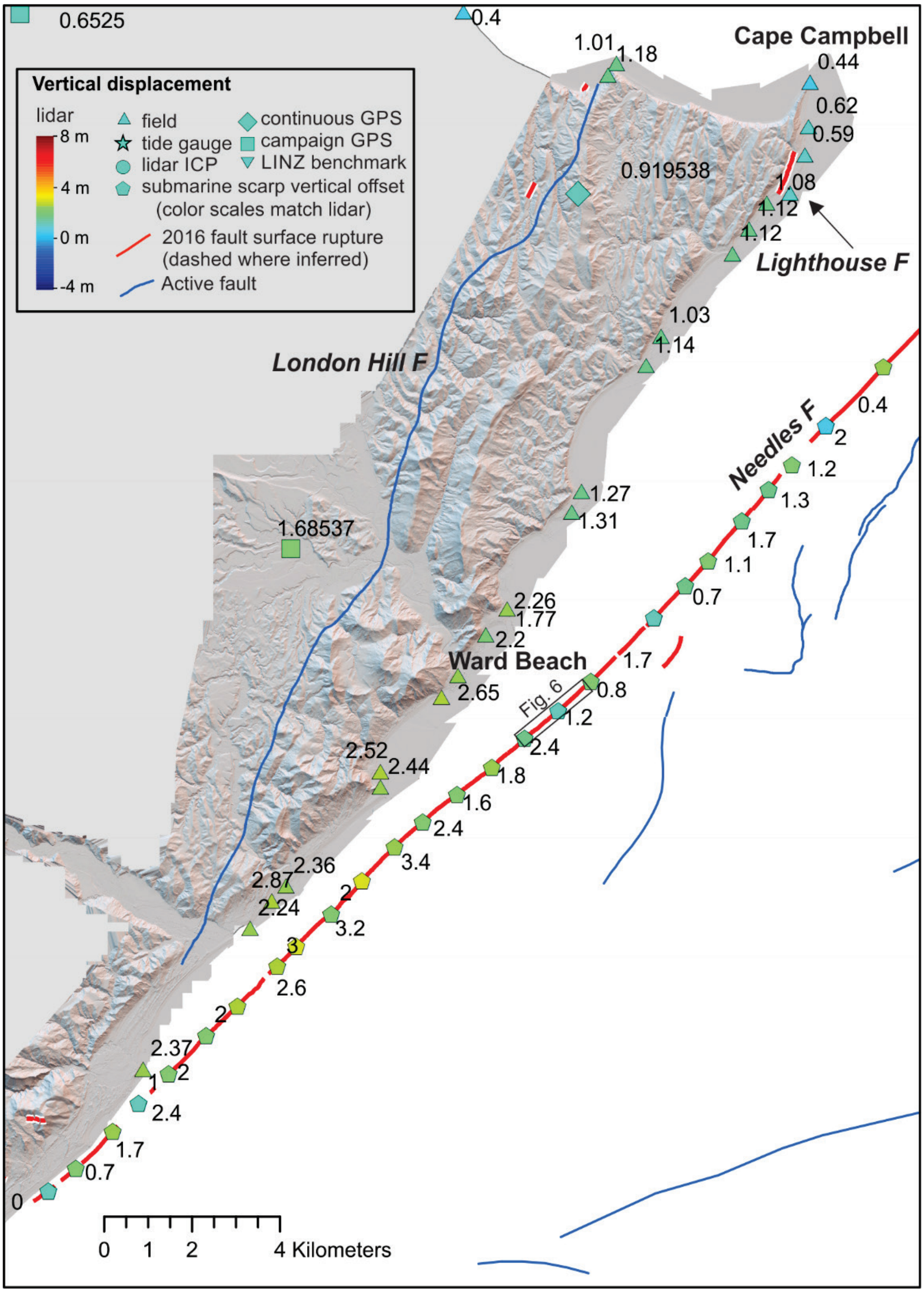


Figure 1.5. Map of 2016 Kaikōura earthquake vertical deformation measurements in the Cape Campbell area. See Clark et al., 2017 for further detail.

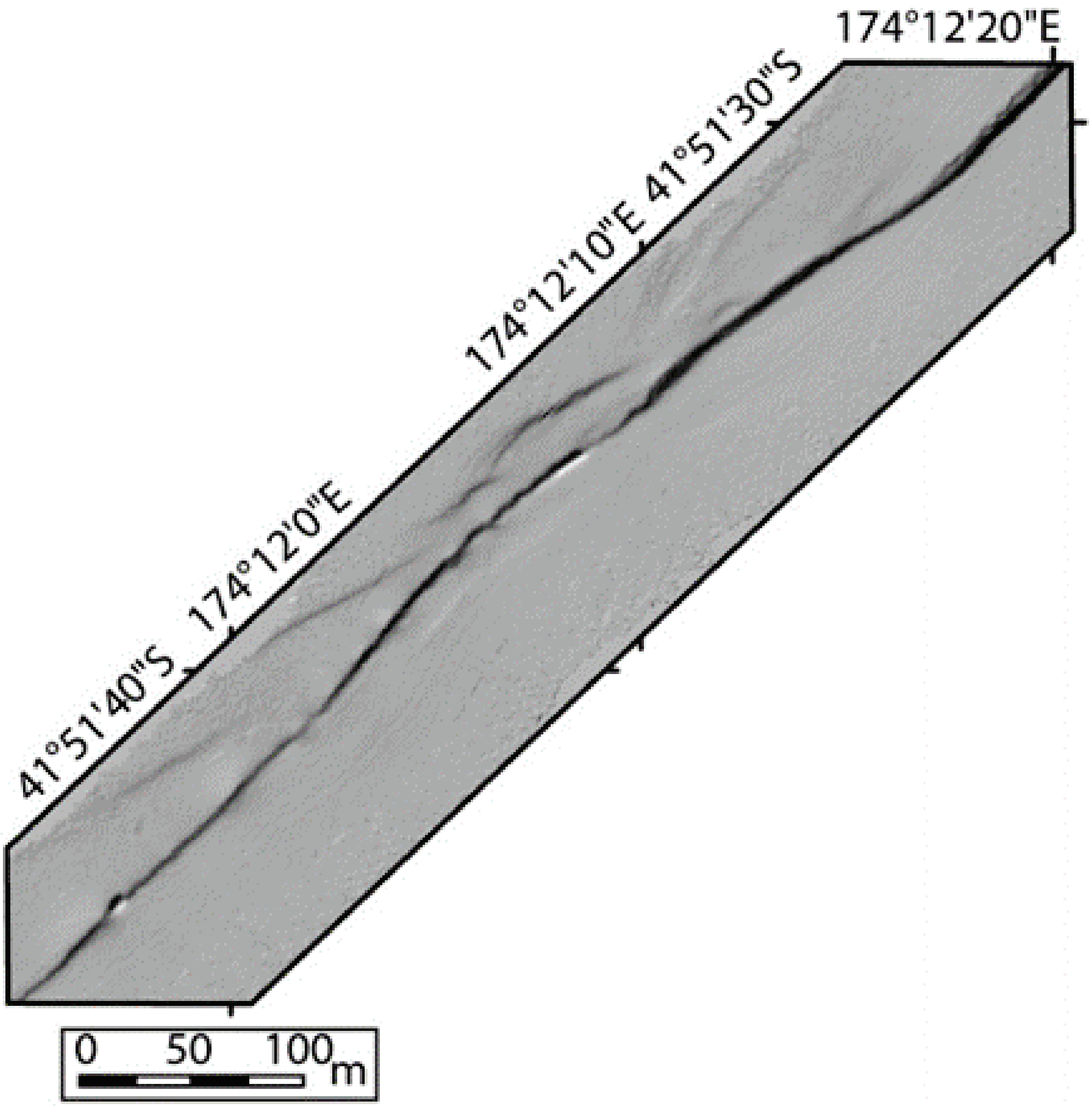
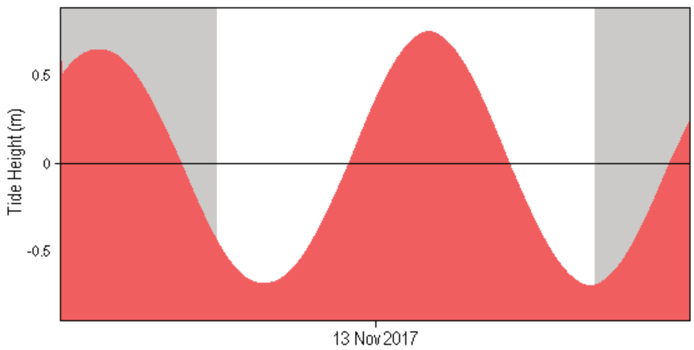


Figure 1.6. Multibeam image of the seafloor trace of the Needles fault directly offshore of Ward Beach (Kearse et al. in review).



2017-11-13	07:38	-0.68
2017-11-13	13:56	0.74
2017-11-13	20:17	-0.69

Figure 1.7. Tide chart for the 13th Nov at Cape Campbell.

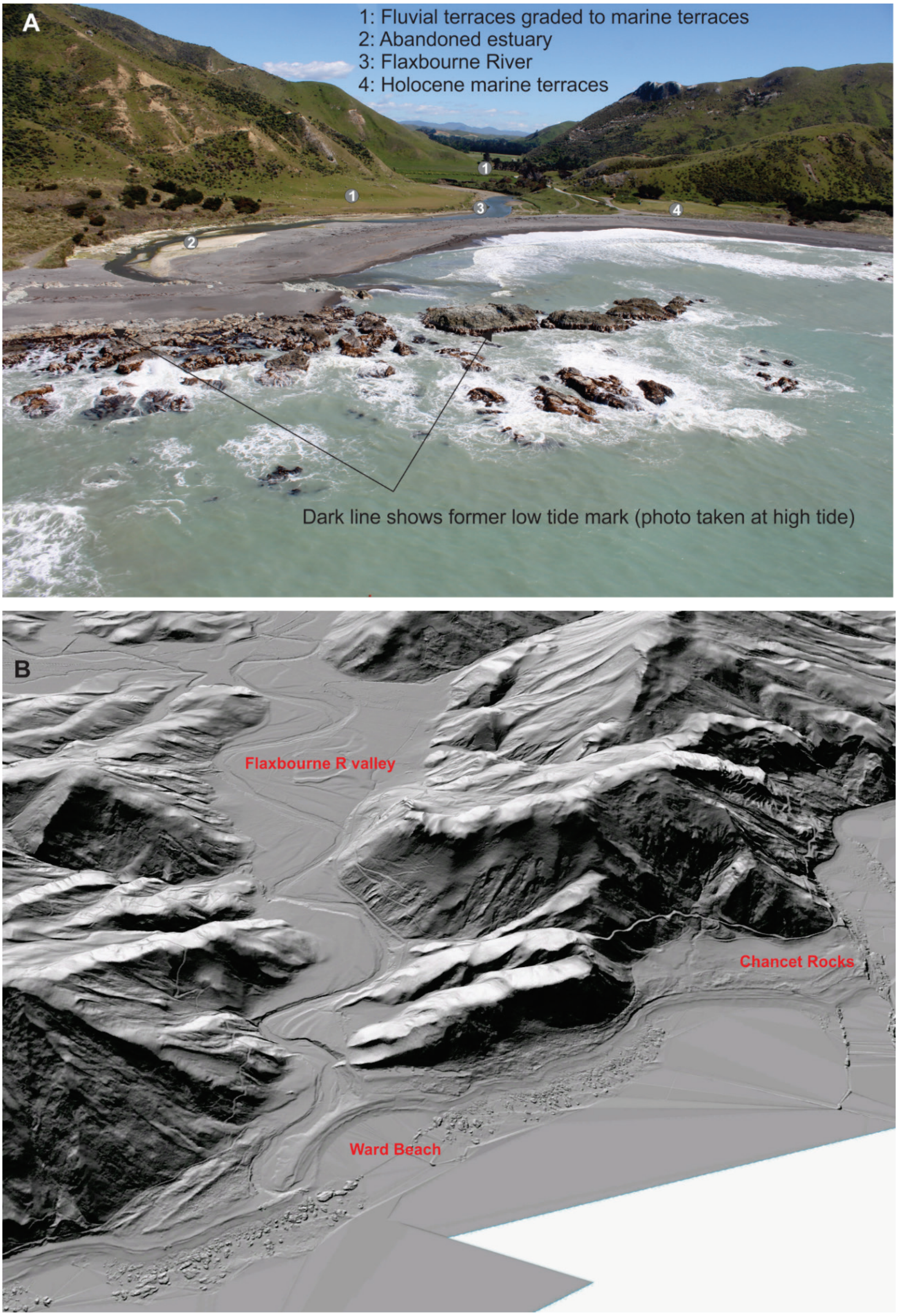


Figure 1.8. Geomorphology of the Ward Beach area showing Holocene fluvial and marine terraces that attest to previous uplift events. (A) Photo taken 4 days after the 2016 Kaikōura earthquake showing the clear line of the top of the bull kelp (marking the pre-earthquake intertidal-subtidal boundary) on the rocks around Ward Beach, photo taken at high tide. (B) Oblique LiDAR hillshade model of the topography at Ward Beach.

STOP 2: KEKERENGU FAULT – BLUFF STATION AND KEKERENGU RIVER

(Leaders: Jesse Kearse, Timothy Little, Russ Van Dissen)

Introduction

The Kekerengu Fault is one of New Zealand's most active on-land faults with a right-lateral slip rate of ~20-26 mm/yr (Van Dissen et al., 2005, 2016) and a recurrence interval of surface rupture earthquakes of ~380 ± 30 yrs (Little et al., in press). As part of the approximately two-dozen strong ensemble of faults that ruptured in the 2016 Mw 7.8 Kaikōura earthquake (e.g. Hamling et al., 2017; Stirling et al., 2017; Litchfield et al., in review), the Kekerengu Fault broke with a maximum net surface rupture displacement of ~12 m, predominantly right-lateral (Kearse et al., in review) making it one of the largest co-seismic surface rupture displacements so far observed globally. The Kekerengu Fault was also one of the faults – along with the Needles Fault along-strike to the NE, and the Jordan Thrust, Upper Kowhai and Manakau faults along-strike to the SW – that collectively comprised the longest (~85 km) and most continuous element of surface rupture in the Kaikōura earthquake (Kearse et al., in review). Prior to 2016, the most recent rupture of the Kekerengu Fault occurred at 110-250 cal yrs. B.P., with two older ruptures documented at 360-538 and 900-1250 cal yrs. B.P. (Little et al., in press).

Stop: Kekerengu River – large right-lateral surface rupture displacements

At this stop (Fig. 2.1), we will walk along the scarp of the Kekerengu Fault where, on 14 November 2016, it ruptured with ~10 m of surface rupture displacement. We will also visit fence lines – once straight – that crossed the surface rupture deformation zone that have been used to document not only the amount of lateral displacement that occurred in 2016, but also the manner in which that displacement was distributed perpendicular to the strike of the surface rupture deformation zone (Fig. 2.2).

Stop: Bluff Cottage – impact of surface fault rupture on a residential structure

Areas that experience permanent ground deformation in earthquakes (e.g., surface fault rupture, slope failure, liquefaction) typically sustain greater levels of damage and loss compared to areas that experience strong ground shaking alone. The Mw 7.8 Kaikōura earthquake generated ≥220 km of surface fault rupture that directly impacted engineered structures and infrastructure (e.g. Stirling et al., 2017; Litchfield et al., in review). The amount and style of surface rupture deformation varied considerably, ranging from decimetre-scale distributed folding to metre-scale discrete rupture, with the severity of damage invariably correlating with both total displacement and strain. About a dozen buildings, typically single-storey timber-framed houses, barns and wool sheds with lightweight roofing material, were directly impacted by surface fault rupture. None of these buildings collapsed; however, all buildings directly impacted by surface faulting suffered greater damage than comparable structures immediately outside the zone of surface rupture deformation. From a life-safety standpoint, all these buildings performed satisfactorily and provide examples of construction styles that could be employed to facilitate non-collapse performance resulting from surface fault rupture (including, of course, strong ground shaking) and, in certain instances, post-event reinstatement/functionality.

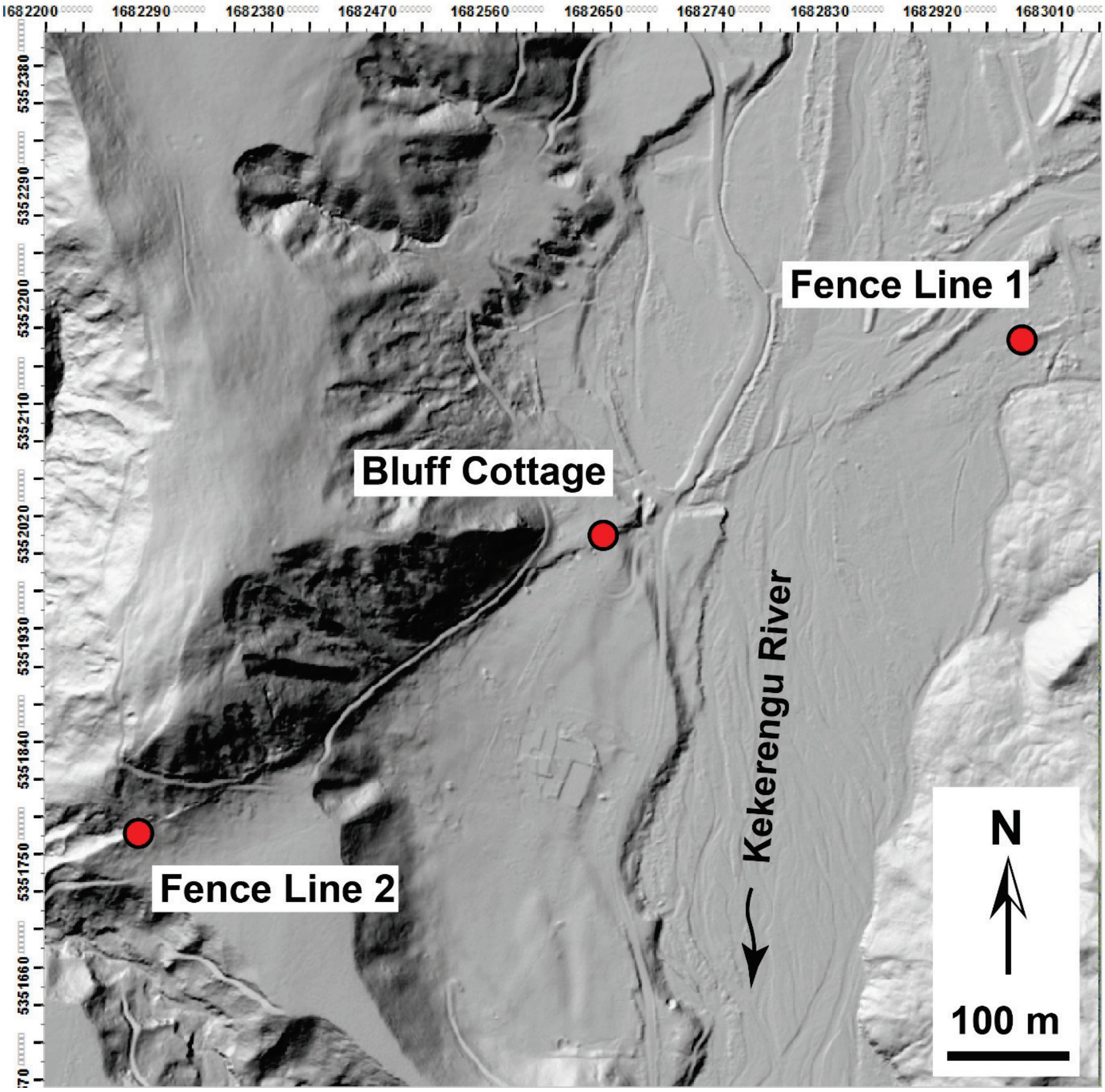


Figure 2.1. Location map for Kekerengu Fault fieldtrip stop. Hillshade image is DEM based on post-earthquake LiDAR, and illuminated from the NW.

Of the residential structures impacted by surface fault rupture during the Kaikōura earthquake, Bluff Cottage (Figs. 2.1 and 2.3) deserves special mention because of its commendable life-safety (non-collapse) performance when subjected to extreme surface fault rupture deformation. Bluff Cottage is a timber framed single story residential structure (house) with a corrugated metal roof, and a combination of timber weather board and concrete brick cladding. It has a roughly rectangular floor plan (area of ~90 m^2), a timber floor comprising a combination of particle board sheets and tongue & groove hardwood strips/planks, and a pre-cast concrete chimney/fireplace (with some reinforcing) encased by concrete brick. It has a concrete perimeter foundation with shallow seated concrete piles. The timber floor joists (150 × 50 mm) are skew nailed to the timber wall plates with the wall plates bolted to the perimeter foundation, and the timber bearers attached to the piles via wire ties.

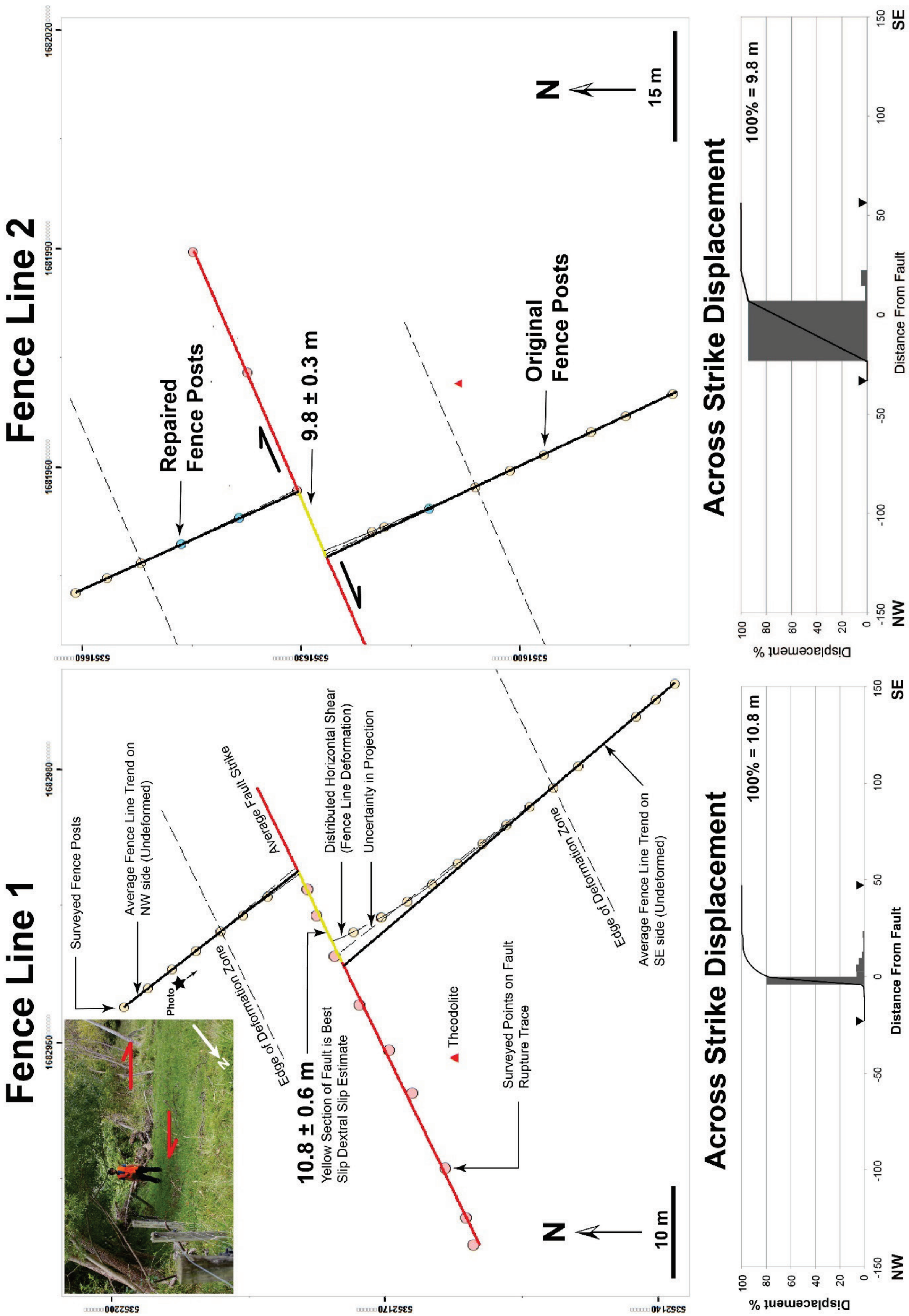


Figure 2.2. Examples of fence line displacements along the Kekerengu Fault documenting both the amount of right-lateral displacement, and how that displacement is distributed as a function of distance perpendicular to fault strike (from Kearse et al., in review). See Figure 2.1 for locations.

Approximately 10 m of discrete (i.e., concentrated – as opposed to distributed) horizontal surface fault rupture displacement extended through the foot-print of Bluff Cottage (Fig. 2.3); subordinate, vertical displacement (up to the NW) also occurred. The foundation of the house was cut in half and right-laterally displaced by fault rupture. The superstructure of the house was low mass, flexible, regular in shape, timber floored and relatively weakly attached to the foundation. These properties allowed the superstructure to detach from the laterally displacing foundation, and to isolate it from the extreme ground deformation taking place beneath. To be sure, the house suffered severe structural damage, but it did not collapse, and the occupant was unharmed. From a life-safety perspective, and considering the large amount and condensed nature of the surface fault rupture deformation at this site (i.e., metre-scale strike-slip displacements and shear strains in the order of 100), this house performed admirably.

On the night of the earthquake, the occupant of Bluff Cottage had just gone to bed when the shaking started. Initially he braced himself in a doorway, but as the shaking intensified he rushed out of the house, jumped off the veranda, and ran into the open paddock/lawn immediately SE of the cottage. It was a full moon and he reports seeing trees violently swaying back and forth, and the power lines spark as they were torn from the cottage. The noise, he says, was incredible, and by his reckoning, about a minute after the shaking started, the ground ruptured through the cottage. He reports that while watching the cottage and struggling to stand, his right leg went up and his left leg went down. Apparently, he was literally standing astride the Kekerengu Fault when surface rupture propagated through this site.

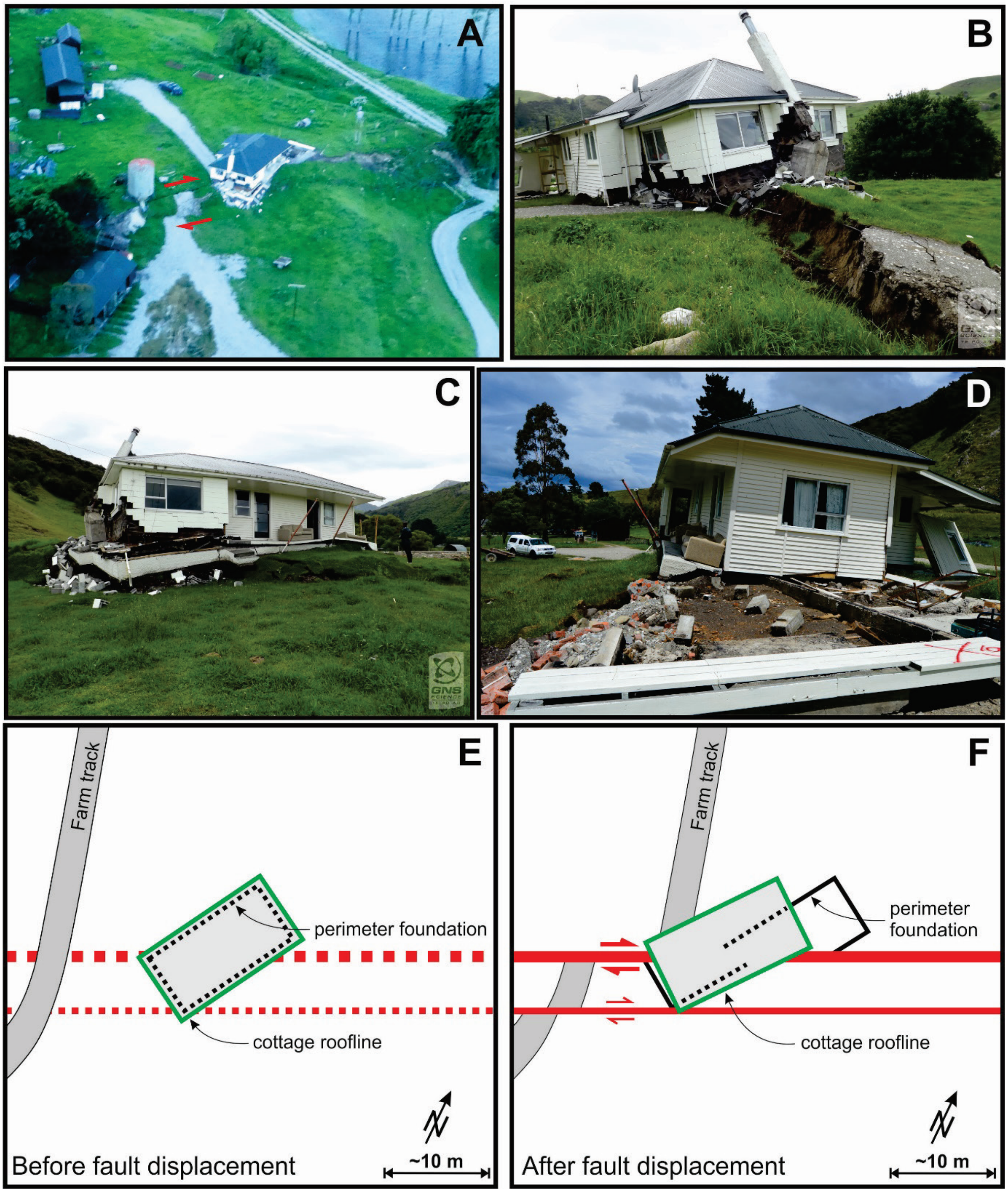


Figure 2.3. Bluff Cottage and Kekerengu Fault. A) Aerial view looking N. Red arrows show sense of slip of the Kekerengu Fault that generated ~10 m of right-lateral surface rupture displacement at this locality. Photo by Timothy Little. B) View of Bluff Cottage looking NE along the strike of the surface rupture of the Kekerengu Fault. Right-laterally offset farm track to left of cottage in Figure 2.3A is the same farm track visible in lower right and middle left of Figure 2.3B. Photo by Nicola Litchfield. C) View looking NW. Photo by Nicola Litchfield. D) View looking SW. Note that the concrete perimeter foundation and piles that were once under the cottage have now been torn from the superstructure of the cottage and strike-slipped towards the viewer relative to the cottage. Photo by Robert Zinke. E) Schematic of Bluff Cottage and farm track prior to surface rupture of the Kekerengu Fault. F) Schematic of cottage and farm track after fault displacement.

STOP 3: NORTH CLARENCE

(Leaders: Rob Langridge And Will Ries)

Seaward overview

We have a safe turnout spot along Clarence Valley Road, c. 1 km NE of Corner Hill which offers good views down to the Papatea Fault, a splinter of the Papatea Fault called the Corner Hill Fault, the Clarence River valley, the Papatea Block, and the high Seaward Kaikōura Range (Fig. 3.1). Some of the features of interest such as the Kekerengu Fault or Waiautoa microblock (Langridge et al., 2017) may be difficult to see from this point, but this spot offers the best view around of the high mountains and an overview of the scope of the faults involved in this part of the earthquake. The main things to look for are:

A. Corner Hill Fault (CHF): about 160 m in front of you. This NNE-striking fault ruptured along a pre-existing feature in 2016 with <1 m net slip. The CHF was recognised before the quake by locals, who called it the 'old fault'. The CHF occurs in the footwall of the Papatea Fault and forms part of a wider Papatea Fault Zone (PFZ; Langridge et al., in review).

B. Papatea Fault: the main strand of the Papatea Fault occurs in the Clarence valley c. 800 m in front of us. At this location, the Papatea Fault forms the western margin of an elongate lake that formed after the Clarence River avulsed onto the downthrown side of the fault. Field estimates of the scarp height (c. 6-7 m) were confirmed by measurements from differential LiDAR (D-LiDAR) that indicate across a width of c. 40 m there were very large throws associated with the fault. The river channel in the background is in the location of the former river which now sits on the hangingwall of the Papatea Fault. Avulsion of the river is obviously one of the major ongoing issues for folk in the valley.

Figure 3.1 View at Stop 3 (Seawards overview). In the foreground is the Corner Hill Fault. In the valley, the scarp of the Papatea Fault forms the side of the lake. In the midground is the low range associated with the Papatea block. In the

distance is the northern end of the Seaward Kaikōura Range, associated with rupture of the Jordan Thrust. The bush-covered shoulder of Middle Hill is at the left edge of the photo.

C. The Papatea block: Hamling et al. (2017) named this fault-bounded block with large vertical and horizontal motions, the Papatea Block. In the mid-ground (1.5 – 2 km away) on the other side of the river we are looking at an uplifted wedge of greywacke bedrock between the main strand (in front of us) and an antithetic strand of the Papatea Fault.

D. Seaward Kaikōura Range (SKR): The Jordan Thrust occurs at the base of the SKR in the distance (Van Dissen, 1989; Van Dissen and Yeats, 1991). Range heights get up to 2283 m a.s.l. (Tarahaka) where we are looking. The only part of that fault that we landed on was in behind Middle Hill. Many other fault offsets have been measured using post-earthquake LiDAR (Kearse et al., in review).

E. Fidget and Kekerengu faults: hard to see from here but the Fidget is tucked over the north edge of the SKR here, following George Stream. The Kekerengu Fault rupture starts out on the north side of George Stream.

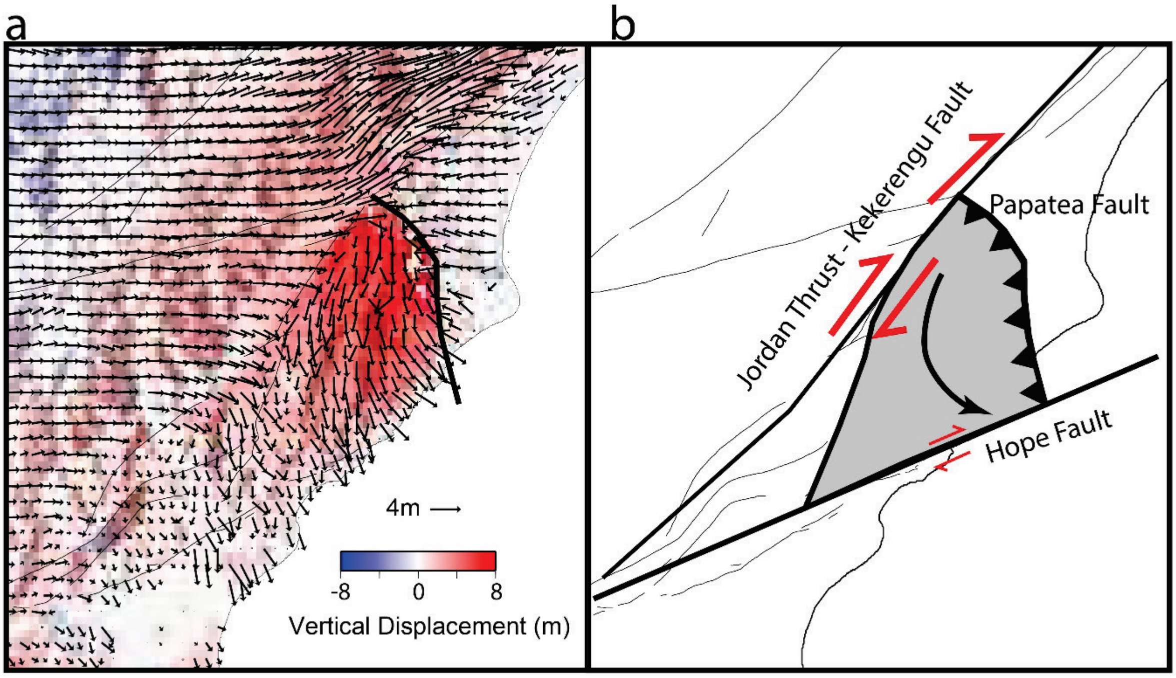


Figure 3.2 Three-dimensional displacement field associated with the Papatea block and schematic model (from Hamling et al., 2017). (A) The 3D displacement field over the Papatea block. Arrows represent the horizontal displacements, and the background shows the vertical displacements. (B) Schematic diagram explaining the cause of the counter-clockwise rotation of the block.

The Papatea Fault and Papatea block are two of the harder components of the 2016 Kaikōura earthquake to rationalise. Figure 3.2 and this stop gives us an opportunity to think and talk about it*

*Current geological research on the Papatea Fault is submitted as a manuscript to the BSSA Special Volume on the Kaikōura earthquake (Langridge et al., in review). Some of what is presented here will appear in that paper.

Priam's Flat

We continue up Clarence Valley Road till we get off the Tertiary hill country and down to an alluvial area, known locally as Priam's Flat (Fig. 3.3). Before the earthquake, Clarence Valley Road went up to the Glen Alton Bridge, which crossed the river and provided access to the Waiautoa area (Fig. 3.4). The bridge was knocked down due to strong ground motion and/or fault displacement on the nearby Papatea and Waiautoa faults (Langridge et al., 2017).

WARNING: EXTREME CAUTION and care is required at this stop. The avulsed Clarence River is a dangerous and unpredictable area. Please stay at least a couple of metres back from river bank edges as we do not know whether they could collapse or be under-cut. Please use gates when available rather than crossing fences, and take care not to disturb any farm animals.

We will walk down toward the river to see the fault scarps. We don't have a lot of time for this stop, so please follow the instructions of your guides and return to the bus when asked – the next bus cannot come along the road until we have driven out.

Figure 3.3. The Papatea Fault in the Priam's Flat area. A. Fault map from the Corner Hill (CH) area to the fallen Glen Alton bridge (GAB). Green dots are stops 3 and 4. Abbreviations: CHF, Corner Hill Fault; CL, 'Clarence Lake'; aCR, avulsed Clarence River; Wk, antithetic 'Wharekiri' strand of the Papatea Fault. B. Avulsed river flows at the base of the fault scarp, which is characterised by en echelon tears in this area. C. large, 7 m high scarp comprised of 2-3 thrust/reverse traces. D. Composite fault scarp along Clarence Lake. Note the definitive strike change at centre.

The stretch of the fault that we are walking along consistently has a throw of c. 6-7 m up-to-the-west (Fig. 3.3c). From Corner Hill to the north, the fault has three distinct pieces that have lengths of 0.7, 1.4 and 1.3 km long from south to north (Fig. 3.3a). Each of these pieces is straight and has a distinct strike change of 10-20º to the next piece (Fig. 3.3d). At Priam's Flat (Fig. 3.3b), the river flows along the base of the fault scarp. This piece of the fault is characterised by a composite scarp with height diminishing from c. 7 m in the south to c. 5 m in the north. The other characteristic of the scarp here are en echelon tears, spaced c. 20-30 m apart, with lengths of up to 100 m. These changes in the strike and character of the surface rupture are telling us something about the dip, slip and stress orientations of the Papatea Fault in this area.

At Priam's Flat, the river has reamed out the scarp in places to expose the alluvial stratigraphy of the valley fill. The stratigraphy ranges from a very thick brown silt up toward the Glen Alton bridge, to cross-bedded pebble gravels opposite Priam's Flat. The river is already developing a meander system adjacent to the scarp, requiring our thoughtful care.

Figure 3.4. Google Earth images of Priam's Flat pre- and post-earthquake. The post-earthquake imagery is from the 21st Nov 2016, and as you will observe, the eastern branch of the Clarence River has since become the main channel of the Clarence River and has eroded a significant amount of farmland,

STOP 4: MIDDLE HILL STATION

(Leaders: Kate Clark And Pilar Villamor)

Apart from at the coast, which we cannot visit on this field trip due to the reconstruction of SH1, the Papatea Fault is best expressed along the northern and southern approaches to Corner Hill. The Papatea ruptures on the west side of the Clarence Valley are accessed via Waipapa Road. We cross the Clarence River bridge on SH1 and turn inland on Waipapa Road (note the NCTIR roadblock!). Along Waipapa Road you will see a sequence of hillsides with very obvious landslides, these hillsides mark the location of the Papatea fault. The largest is the 18 M m3 Seafront Landslide, which cannot be seen from the road (Massey et al., BSSA in review). Farther along Waipapa Rd we pass by the toe of the Limestone Hills Landslide and a paleo-landslide, which is perhaps an indicator of the penultimate shaking event or fault rupture related to the Papatea Fault.

From the limestone quarry, we are essentially driving along the scarp of the Papatea fault. On this property **please take care not to enter any paddocks with deer in them, this is very important!**

We will start our walk of the fault from Miller Stream. We will walk down Miller Stream to the Clarence River and then follow the fault scarp back around to the farm track. You will be given a safety briefing before this part of the trip – hazards include uneven ground, a very fast-flowing river, unstable river banks, and large ground fissures. Please take the time to look where you are placing your feet, rather than looking through your camera.

The largest vertical throws along the Papatea Fault are recorded along this stretch of the fault. Throw increases from a mere 6 m at the Waipapa Quarry to almost 10 m adjacent to the Middle Hill Station (MHS) homestead (Fig. 4.1b). The landowner at MHS assured us that prior to the earthquake the farm track to Miller Stream (crossing the fault zone) was flat before the earthquake. D-LiDAR indicates that this is at least 8 m of throw (near the river). The rupture is complex and comprises overlapping reverse and thrust fault traces.

One feature of the fault in this area are that there are elevated alluvial terraces (labelled T1 and T2) preserved on the hangingwall side of the fault. The fault forms an escarpment here with T1 and T2 elevated by c. 30 and 18 m above the terrace on the footwall side of the fault. These terraces offer a potential to consider the paleoearthquake or paleo-slip history of the Papatea Fault.

Figure 4.1 The Papatea Fault in the Middle Hill area. A. Rupture map from the Waipapa Quarry (WLQ) area to the Clarence River crossing near Corner Hill (CH) presented on a post-earthquake LiDAR hillshade model. Green dot is Stop 5 at Middle Hill Station (MHS). Asterisks mark the photo centres for B, C and D. T1 and T2 are two terraces elevated on the hangingwall side of the Papatea Fault. Abbreviation: p-ls, paleo-landslide deposit. B. Reverse and thrust fault rupture traces in front of MHS. C. Rupture traces progressing from MHS to the Clarence River; note the highly uplifted beds of the co-joined Miller and Wharekiri streams. D. Papatea Fault exposure on the NE bank of the Clarence River. Note the pair of rupture planes, and the uplift markers both within the fault zone and upstream where Amuri limestone bedrock has been uplifted. The red arrows mark two distinct fault zones (or the width of the entire fault zone).

Near the Miller Stream track, we observe a hangingwall graben as part of the rupture. At the confluence of Miller and Wharekiri streams their floodplains have been uplifted by c. 8 m and their channels have entrenched themselves rapidly to the new base level created by faulting (Fig. 4.1c). Upon reaching the new true right bank of the Clarence River you get a sense of how much throw there has been. You can also look across to one of the few exposures of the Papatea Fault (Fig. 4.1d). At this locality, an apparent attitude of 180/46º W has been measured. This observation and three-point problems indicate that the fault dip is moderate. In this exposure Paleogene Amuri limestone is overthrusting Miocene Waima siltstone and ‘Great Marlborough Conglomerate’.

LIST OF RELEVANT PAPERS TO BE FOUND IN FOLDERS IN THE BUSES

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