Kaikōura Earthquake Short-Term Project

Title: Inventories of onshore surface fault ruptures and coastal uplift

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DISCLAIMER

BIBLIOGRAPHIC REFERENCE

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ABSTRACT

Ground deformation in the 14th November 2016 magnitude 7.8 Kaikōura Earthquake was extra-ordinarily complex, including multiple (>20) ground-surface fault ruptures and extensive (>110 km) coastal uplift. This report documents work undertaken after the initial GeoNet response phase to document the ground-surface fault ruptures and coastal uplift, with a large focus on high resolution topographic (Light Detecting and Ranging) data. This work provides essential information for better understand what happened in the earthquake, and to inform future seismic hazard and land use planning.

Key findings for the coastal deformation are that it was highly variable along the coast, ranging from uplift of 6.5 m to subsidence (land drop) of 2.5 m. The coastal deformation is almost all the result of movement on crustal faults, including one beneath Kaikōura Peninsula.

Ground-surface fault ruptures have now been documented on 24 faults, about half of which were not recognised as active faults before the earthquake. About a third were included in the 2010 version of the New Zealand National Seismic Hazard Model, including a multi-fault source. Maximum ground-surface fault displacement was ~12 m on the Kekerengu Fault, but slip distributions show that the displacement varied along the faults, as documented on other ground-surface fault ruptures from around the globe.

Future work includes paleoseismological studies to obtain information on the timing and magnitude of past earthquakes. This information will be used to better characterise multi-fault ruptures and incorporation of time dependent seismic hazard in seismic hazard models.

KEYWORDS

Kaikōura Earthquake, Marlborough, North Canterbury, Coastal deformation, Ground-surface rupture, Active fault.

1.0 INTRODUCTION

The 14th November 2016 magnitude 7.8 Kaikōura Earthquake was unprecedented in having multiple (>17) onshore ground-surface fault ruptures and extensive (>110 km) coastal uplift. In the weeks following the earthquake a large field team (>50), coordinated through the GeoNet response, was busy in the field identifying faults that broke the ground surface and measuring permanent ground movement using cultural markers (e.g., fences, roads) and low-tidal biota (e.g., bull kelp and other types of seaweed). However, because of the large area and the complexity of the ground deformation, extra funding was needed to complete the fieldwork and to undertake office-based analysis of all the data, particularly of the Light Detecting and Ranging (LiDAR[1]) high resolution topographic data, which was accomplished in this project.

This work was essential to document the ground surface deformation that happened in the earthquake, to better understand plate boundary tectonic processes and how the faults should be modelled/characterised for future earthquake hazard, and to inform future land use planning. It was also urgent because: 1) some of the ground movement features were being removed by farmers reinstating their land or through natural erosion; 2) the information was needed to inform forecasts of what might happen next; and 3) stakeholders (e.g., Councils) needed accurate maps of permanent ground deformation for the rebuild and planning.

The key tasks undertaken were:

1. Complete field mapping and surveying, prioritising fragile and/or perishable data;
2. Undertake office-based detailed mapping and analysis of fault traces and coastal uplift;
3. Measure fault displacements and uplift at key locations; and
4. Compile data into definitive inventories of fault traces and coastal uplift.

[1] LiDAR is a surveying method that measures distances using a laser. The data used in this project was collected in December 2016 from an aeroplane and made into high resolution topographic maps. Parts of the area (e.g., along state highway 1) had LiDAR data collected before the earthquake, and by overlaying that with the post-earthquake LiDAR data (differencing) allowed the change in ground elevation to be accurately measured.

2.0 KEY FINDINGS

2.1 COASTAL DEFORMATION

Field observations (Figure 2.1) had shown variable deformation of the coast in the Kaikōura Earthquake, but the detail of that variability was really illuminated from the comparison of LiDAR data collected before and after the earthquake (Figures 2.2 and 2.3) (Clark et al. 2017). For example, it showed areas of subsidence (drop of the land) which were suspected but unable to be measured in the field.

Figure 2.1 Examples of coastal vertical deformation resulting from the Kaikōura Earthquake. a) Uplift (~0.4 m) at Lake Grassmere out-take marked by bands of pre-earthquake (light green) and post-earthquake (dark green) lichen. b) Subsidence (drop, ~2.5 m) marked by ponded water (now drained) at the Kekerengu Fault (denoted by the red arrows). c) Uplift (~4.5 m) at Waipapa Bay between two strands of the Papatea Fault marked by dying sub-tidal kelp now above high tide. d) Close up of the Bull Kelp used to measure uplift in the field. e) Uplift (~1.5 m) at Goose Bay near the Hundalee Fault marked by dying bull kelp. f) Newly exposed rocks at high tide at Kaikōura Peninsula, marking ~1 m of uplift. Modified from Clark et al. (2017).

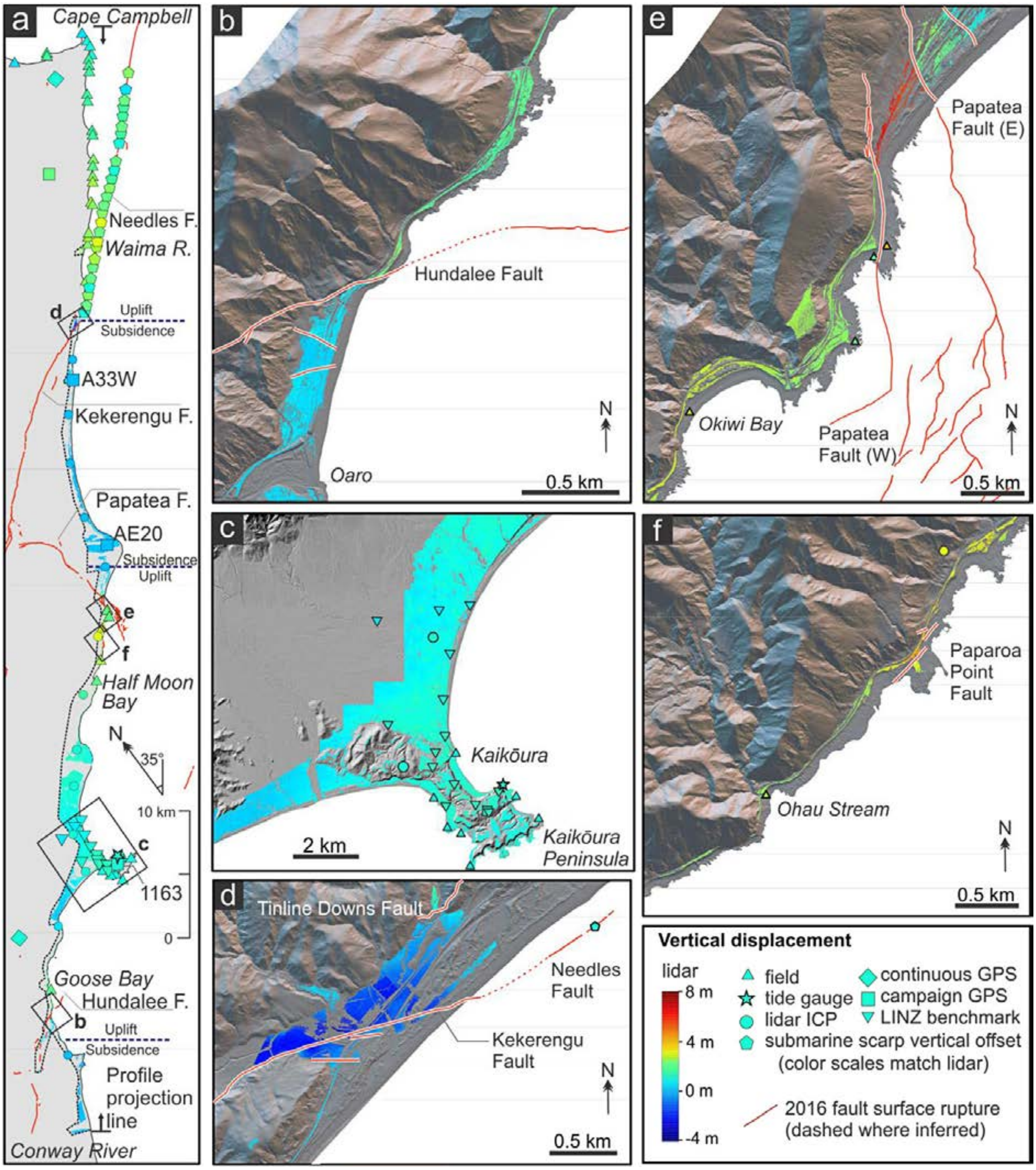

Figure 2.2 Maps of vertical deformation of the coast due to the Kaikōura Earthquake. a) Map of the entire coastline affected. The dashed line is the extent of the pre- and post-earthquake LiDAR data that were differenced to make many of the coastal deformation measurements. b-f) Detailed maps of selected sites, particularly near the ground-surface fault ruptures. From Clark et al. (2017).

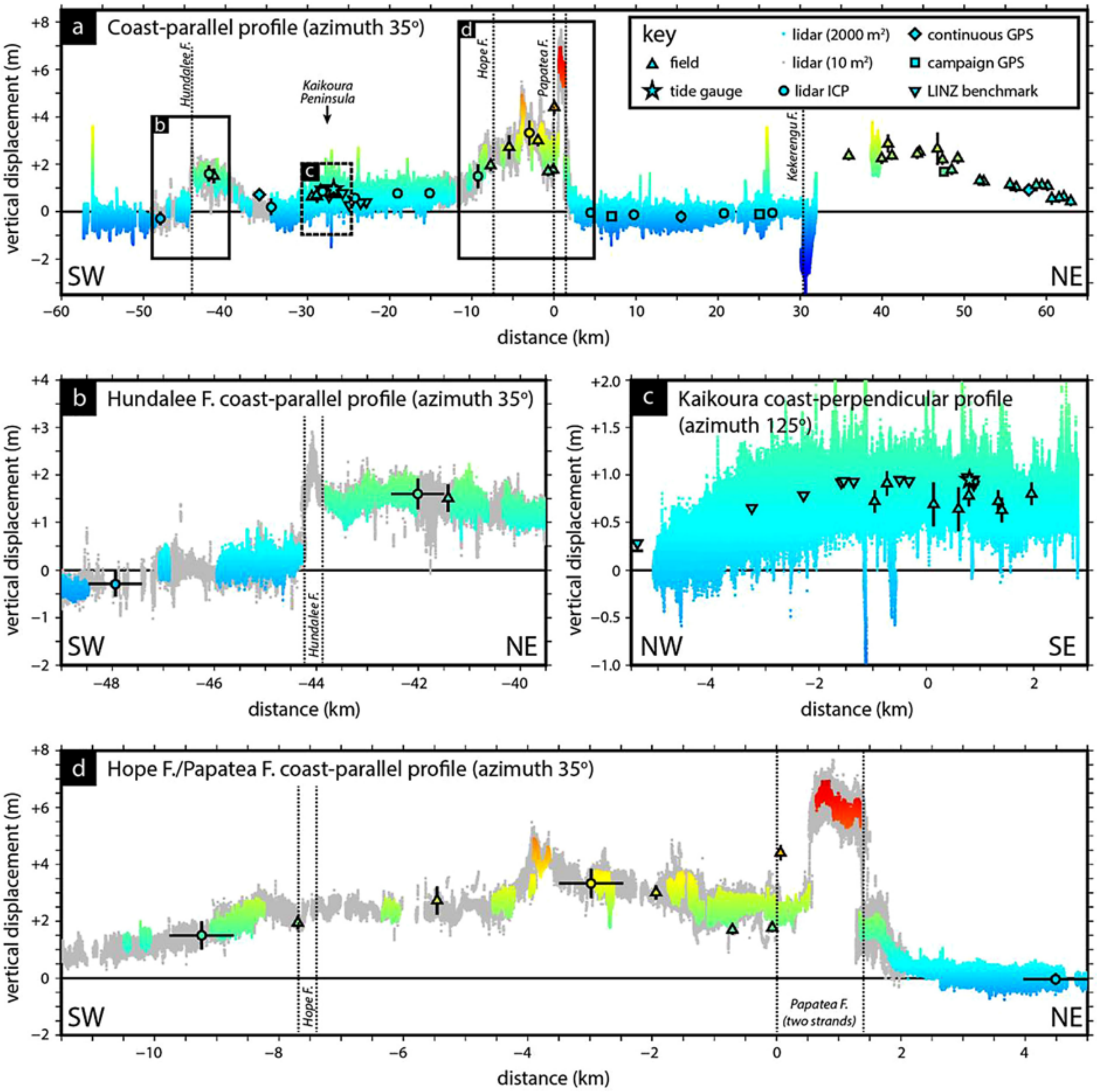

Figure 2.3 Profiles of vertical deformation along the coast due to the Kaikōura Earthquake. a) The entire coast affected, from the Conway River (left) to Cape Campbell (right). b) Close-up profile of the coast either side of the Hundalee Fault. c) Profile from Kaikōura Peninsula to the Coastal Plain. d) Close-up profile across the Hope and Papatea faults. From Clark et al. (2017).

The largest uplift of the coast, of ~6.5 m, occurred at Waipapa Bay, between two strands of the Papatea Fault (Figures 2.1c, 2.2e, 2.3a, 2.3d). The largest subsidence was ~2.5 m at the Kekerengu Fault (Figures 2.1b, 2.2d, 2.3a). Other areas of notable coastal uplift are between the Hope and Papatea Faults (2-4 m) and north of the Kekerengu Fault (3 m in the south to ~0.4 m at Cape Campbell and the Lake Grassmere saltworks) (Figures 2.1a, 2.2a, 2.3a).

Comparison of the location and amount of coastal deformation with the fault rupture data and models from other datasets (e.g., geodesy) shows that the coastal uplift is almost all the result of movement on crustal faults that ruptured in the earthquake, particularly the Hundalee, Papatea, and Needles faults. A broad area of uplift including Kaikōura Peninsula (~1 m) and the Kaikōura Plains (~0.8 m) (Figure 2.2f) is inferred to be the result of rupture of an offshore fault that dips to the northwest underneath Kaikōura Peninsula; this offshore fault may be related to the Point Kean Fault which was identified by a NIWA post-earthquake bathymetry survey. The identification of the offshore fault using the coastal uplift data has also been useful for modelling the tsunami generated by the Kaikōura Earthquake.

2.2 GROUND-SURFACE FAULT RUPTURE MAPPING

Additional field mapping (Pettinga et al. 2017; Litchfield et al. submitted; Kearse et al. submitted; Williams et al. submitted; Nicol et al. submitted; Langridge et al. in prep.; Figure 2.4) and analysis of high resolution datasets such as LiDAR (Figures 2.5, 2.6) revealed even more faults had ruptured to the ground surface in the Kaikōura Earthquake than we initially detected from the first 3 months of fieldwork – the total number of faults now being 24 (Figure 2.7; Litchfield et al. submitted). This is a world record, although some caution needs to be taken in that the number is partly dependent on how faults have been defined. For example, the Kaikōura Earthquake has called into question whether some faults as previously mapped are in fact parts of larger faults (e.g., the Kekerengu and Needles faults are part of one larger fault).

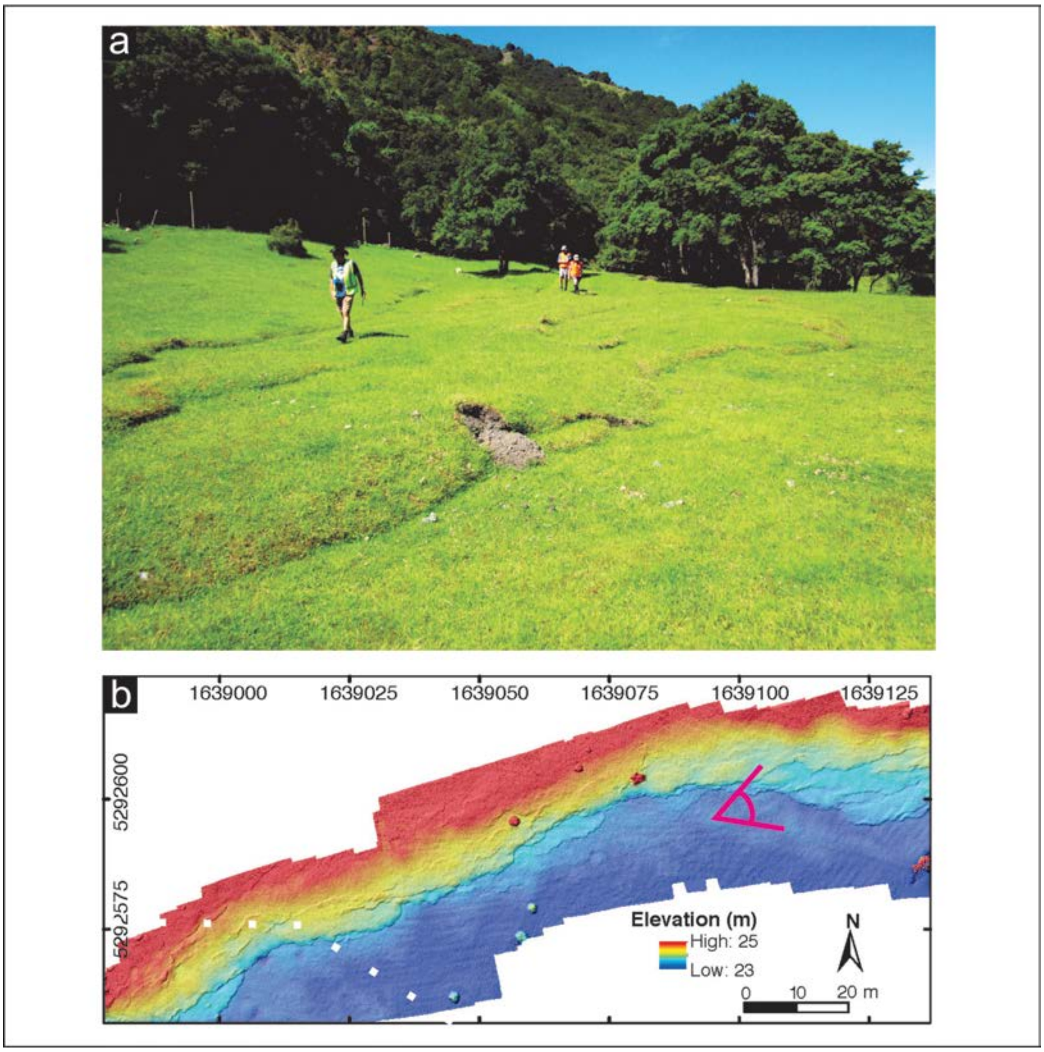

Figure 2.4 a) Field mapping of the Hundalee Fault ground-surface fault rupture by the GNS Science Dunedin and University of Otago team. The ground-surface fault rupture is expressed as rolls of the soil (termed "turf rolls"). b) A high-resolution map of the same part of the Hundalee Fault rupture, made from photos collected by an Unmanned Aerial Vehicle (UAV). From Williams et al. (submitted).

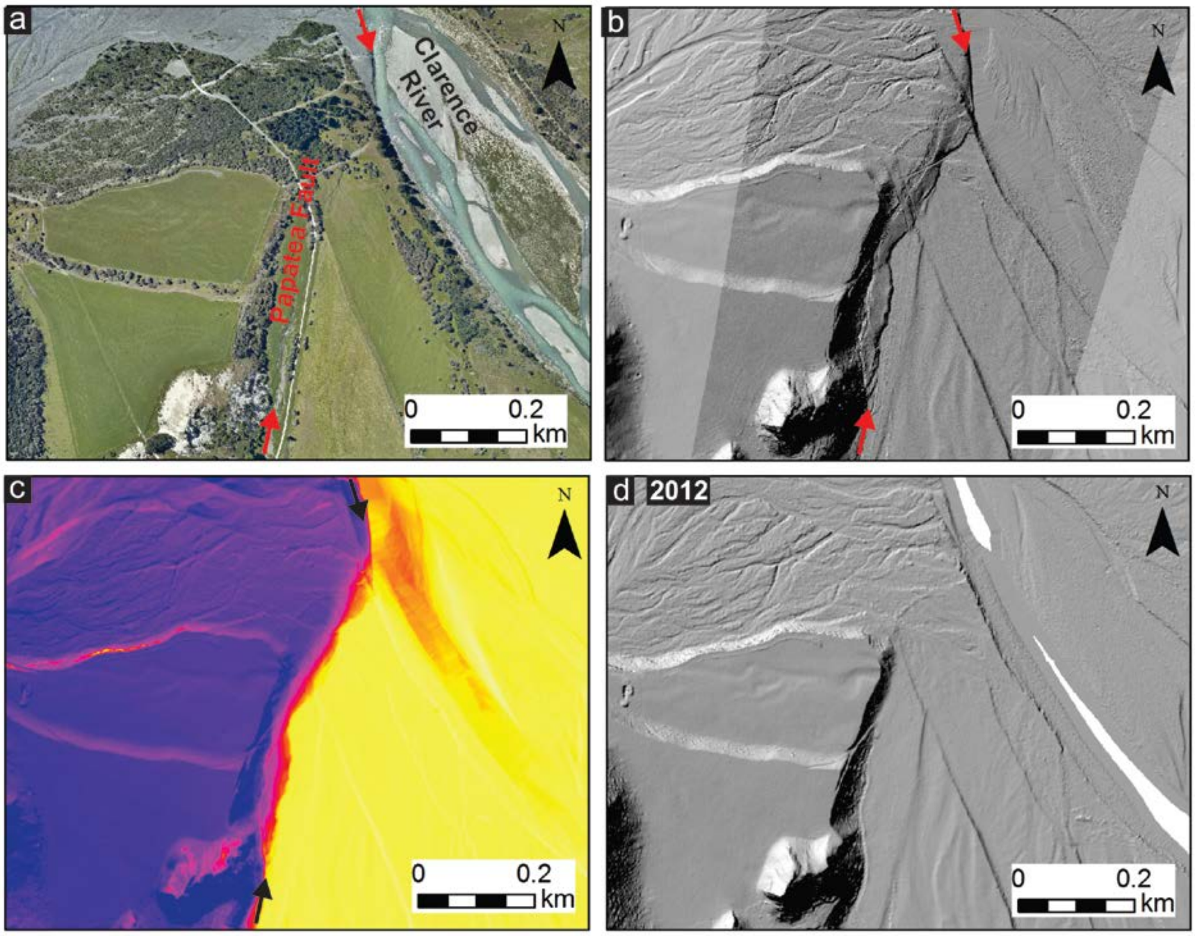

Figure 2.5 Papatea Fault traces (marked by arrows) shown by: a) aerial photographs collected during the LiDAR survey in December 2016; b) a 20 cm resolution LiDAR map (dark grey central area; the remainder is 1 m resolution); c) an elevation difference map between the 2016 (b) and 2012 (d) LiDAR. The pink-purple area has gone up (uplift), and the yellow area has gone down (subsided). Note the absence of Papatea Fault traces in the 2012 (pre-earthquake) LiDAR (d). This is because the evidence for ruptures from previous earthquakes has been eroded away and/or buried by the Clarence River.

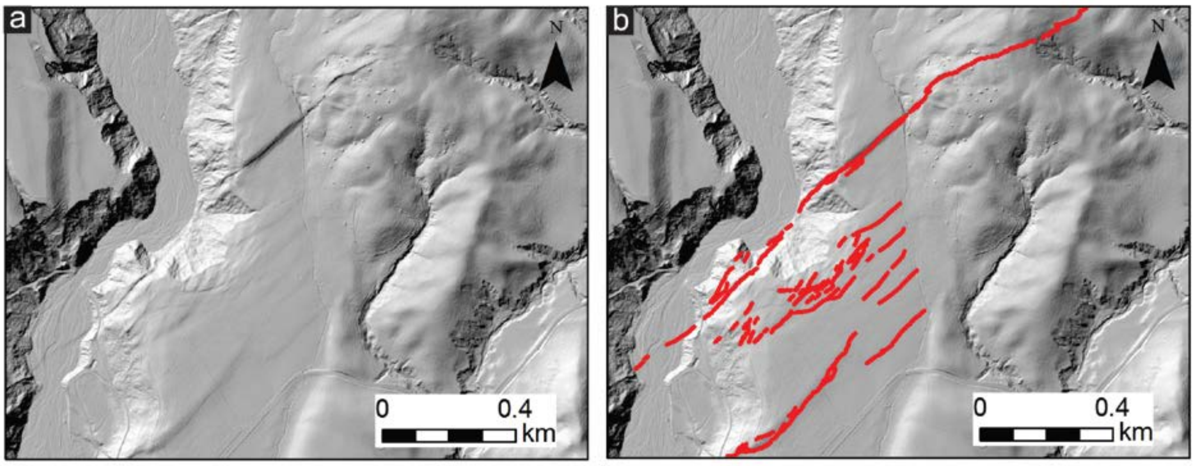

Figure 2.6 a) LiDAR data showing the Conway-Charwell Fault Zone ground-surface fault rupture. b) Detailed fault mapping (red lines) by the University of Canterbury team using the LiDAR and field datasets.

About half of the faults (those labelled with grey boxes on Figure 2.7) that ruptured the ground surface were not recognised as active faults before the Kaikōura Earthquake. One reason for this is that some of the faults have low slip rates (Litchfield et al. submitted), and so evidence for past earthquake ruptures were eroded away or buried by sediments (Figure 2.5d). Another

is that scarps from previous earthquakes may have been too small to still be detectable in the landscape (e.g., along the Marfells Beach, Cape Campbell Road, or Lighthouse Faults).

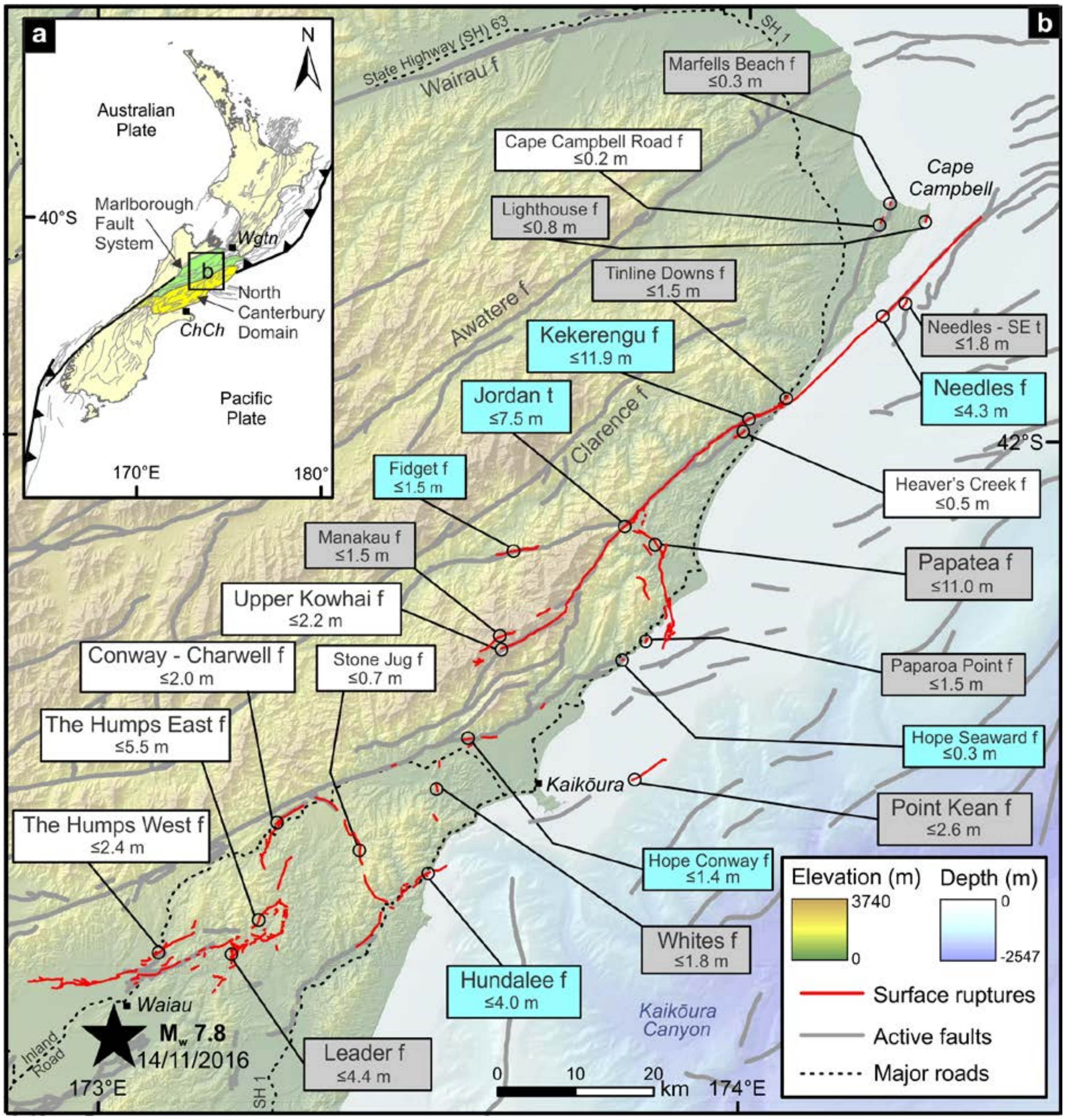

Figure 2.7 a) Major active faults in New Zealand showing the general location of the Kaikōura Earthquake ground-surface fault ruptures, in the North Canterbury Domain and the Marlborough Fault System (Litchfield et al. 2014). b) Faults that ruptured to the ground surface / seafloor in the Kaikōura Earthquake as mapped in this project. For each fault the maximum ground-surface displacement measured from field, swath bathymetry, or LiDAR data is given. White and cyan boxes denote faults that were recognised as active prior to the Kaikōura Earthquake, with the cyan boxes denoting faults that were included as active fault earthquake sources in the 2010 version of the New Zealand National Seismic Hazard Model (Stirling et al., 2012, 2017), Grey boxes are faults not recognised as active before the Kaikōura Earthquake. Modified from Litchfield et al. (submitted).

About a third of the faults that ruptured had been included as active fault earthquake sources in the 2010 version of the New Zealand National Seismic Hazard Model (NSHM; Stirling et al. 2012) (Figures 2.7 and 2.8; Stirling et al. 2017). This included a multi-fault source comprising the Jordan Thrust, Kekerengu, and Needles faults (red line in Figure 2.8). This means that the complexity of the Kaikōura Earthquake was at least in-part anticipated/encrypted in the 2010

NSHM. The Kaikōura Earthquake ground-surface fault rupture however does highlight the need to incorporate more of these multi-segment ruptures in future NSHM developments, and that is already started through the development of a specific Kaikōura Seismic Hazard Model.

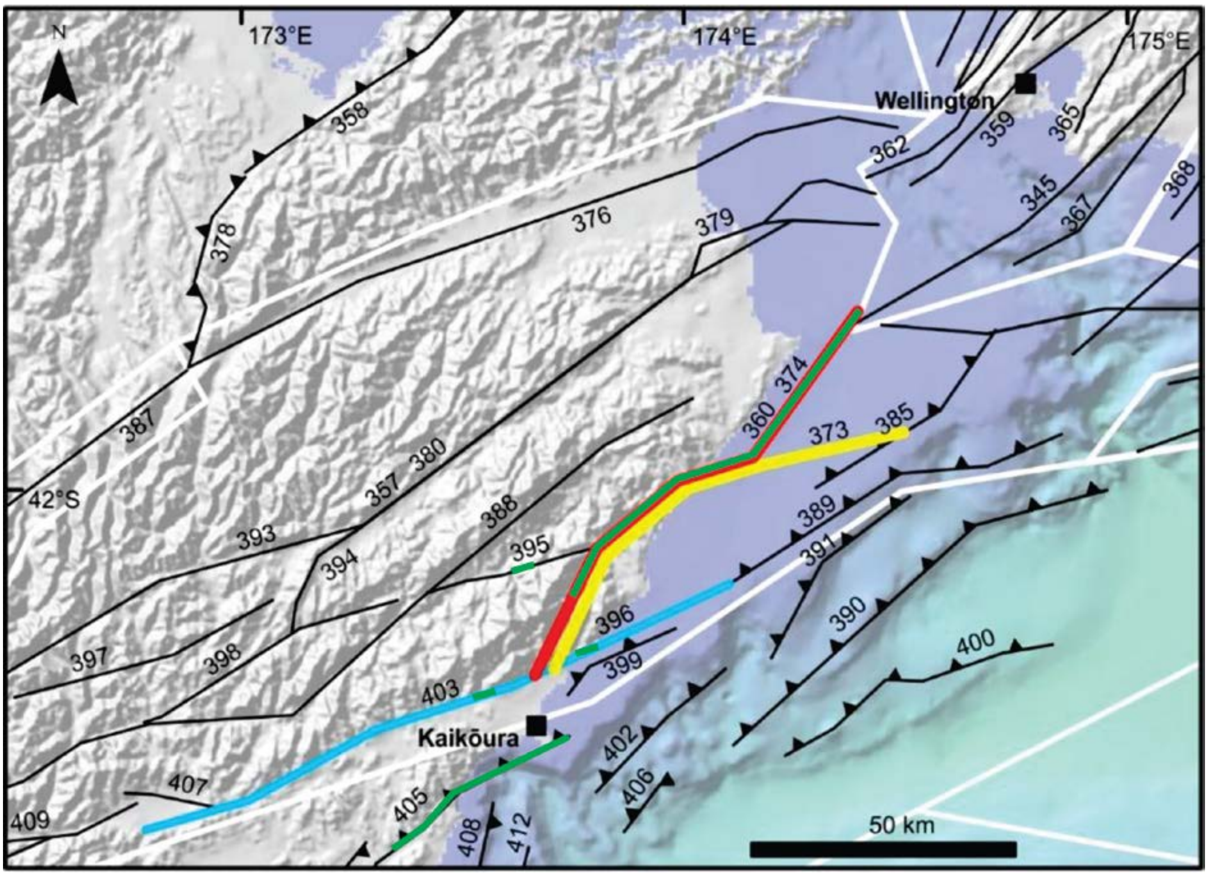

Figure 2.8 Fault sources in the 2010 NSHM in the area of the Kaikōura Earthquake. The sources, or parts of sources, that ruptured in the Kaikōura Earthquake are shown in green. Red, yellow, and blue sources are multi-fault sources. Modified from Stirling et al. (2017).

2.3 GROUND-SURFACE FAULT RUPTURE DISPLACEMENTS

The displacement of the ground surface by fault rupture has been measured at selected sites along the major faults using field surveys (e.g., of fences or roads) or office analysis of data (e.g., swath bathymetry or LiDAR). An example of how the displacements are measured is shown in Figure 2.9.

On Figure 2.7, maximum displacements for each fault are shown below the fault. The largest measured is ~11.8 m on the Kekerengu Fault, with other notably large ones being ~11 m on the Papatea Fault, and ~7.5 m on the Jordan Thrust (Litchfield et al. submitted; Kearse et al. submitted; Langridge et al. in preparation). These are amongst some of the largest crustal fault displacements world-wide, the largest ever being ~19 m in the 1855 magnitude 8.1 Wairarapa Earthquake (Rodgers and Little 2006). In general, the largest displacements occurred on major faults in the Marlborough Fault System, where the earthquake's energy release was greatest (e.g., Kaiser et al. 2107; Holden et al. 2017). Small (<1.5 m) displacements occurred on a number of short traces of larger faults, the most notable being the Hope Fault, which is a major fault that only experienced small-scale rupture to the ground surface in a few localised places (Figure 2.7).

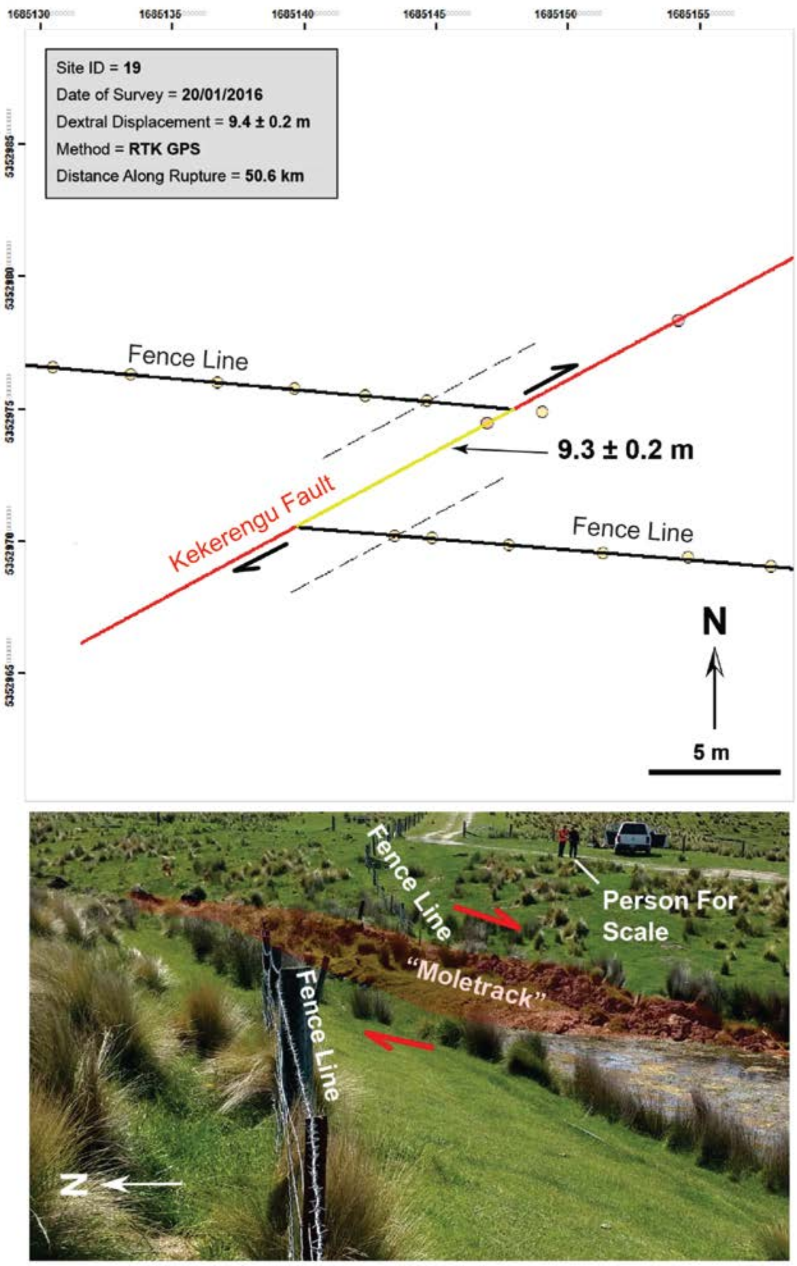

Figure 2.9 Example of the measurement of horizontal displacement along the Kekerengu Fault using an offset fence line. A straight line is drawn through the surveyed locations of the fence posts and projected into the fault. The displacement (~9 m) is then measured from the distance between the intersection points with the fault. Modified from Kearse et al. (submitted).

Slip distribution profiles have been compiled for most of the major faults. Three examples are shown in Figures 2.10, 2.11, and 2.12. Analysis of these profiles is still being undertaken, but in general they are similar to those from earthquakes elsewhere – the displacement locally varies along the length, and the maximum is not necessarily at the centre. Some of the variation is because of rupture on other nearby faults (e.g., there is a change in displacement at the junction with the Papatea Fault junction in the Upper Kowhai to Needles faults profile in Figure 2.10). As well as displaying the variation, these profiles also allow calculation of the average displacement, which in the case of the Upper Kowhai / Manakau, Jordan Thrust, Kekerengu and Needles Faults, is approximately 6 m (Kearse et al. submitted).

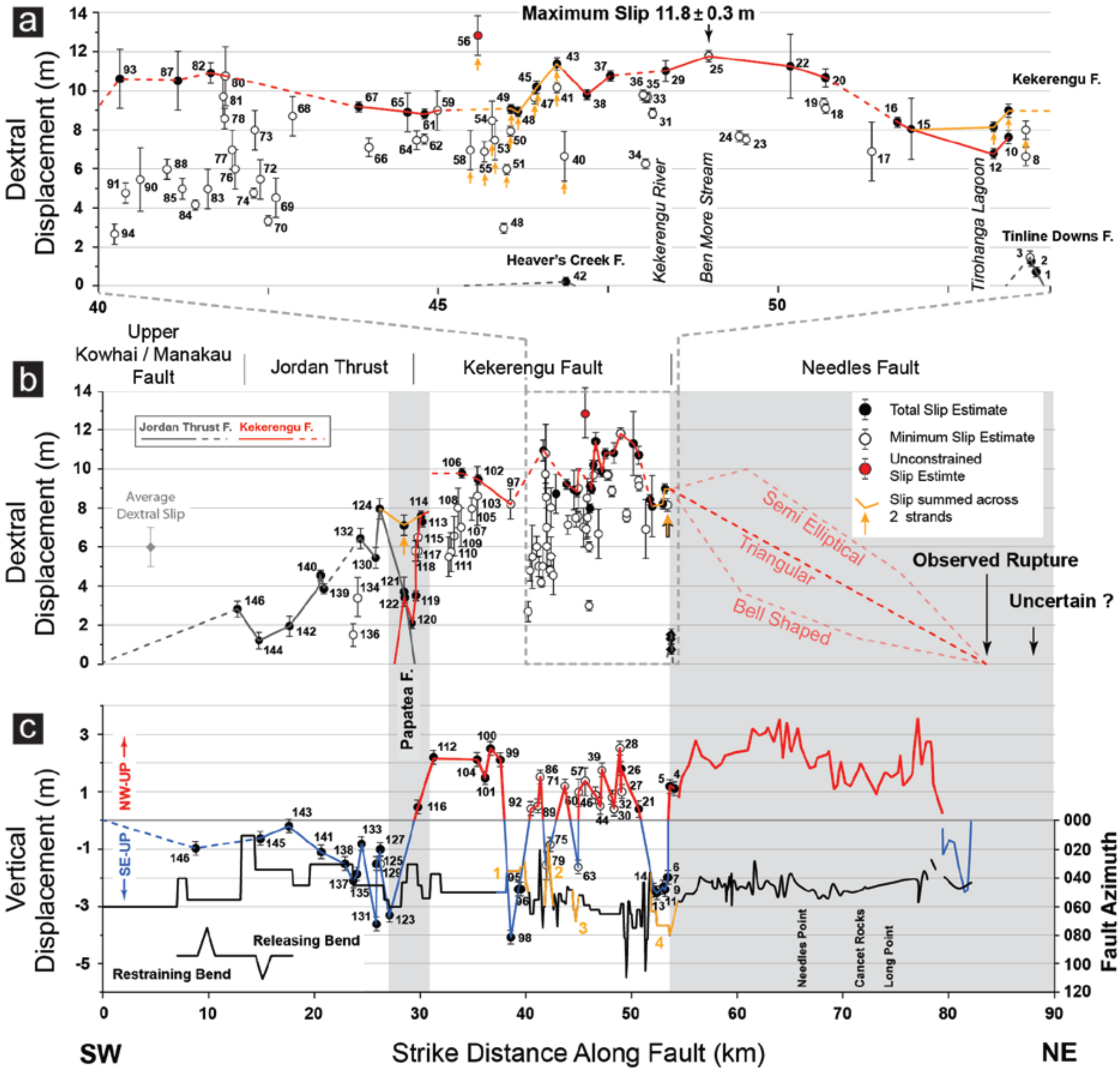

Figure 2.10 Slip distribution profiles for the Upper Kowhai / Manakau, Jordan Thrust, Kekerengu and Needles faults. a) Horizontal displacements along the Kekerengu Fault. b) Horizontal displacement along the Upper Kowhai / Manakau, Jordan Thrust, and Kekerengu faults. c) Vertical displacement along the Upper Kowhai / Manakau, Jordan Thrust, Kekerengu and Needles faults. From Kearse et al. (submitted).

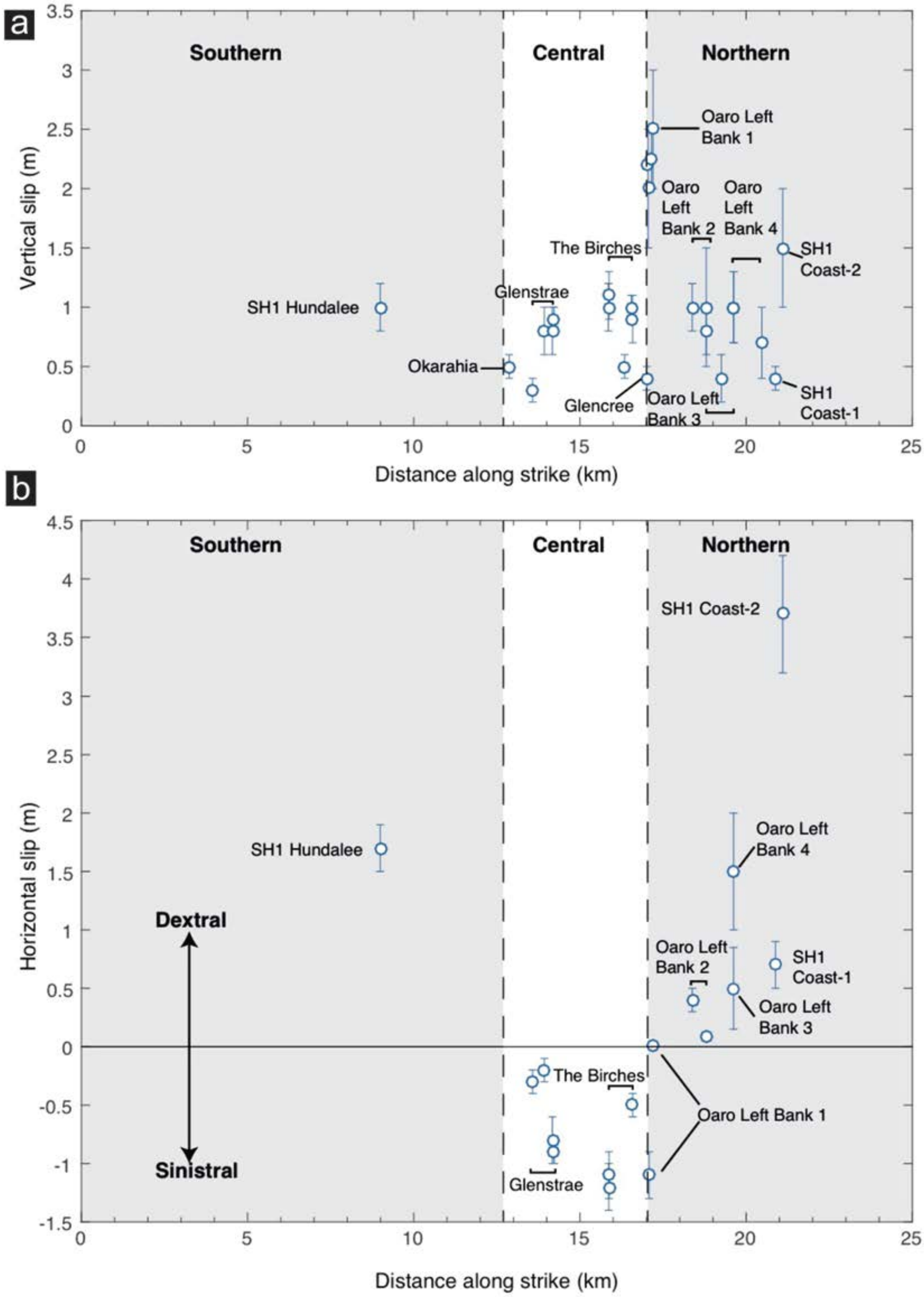

Figure 2.11 Slip distribution profiles for the Hundalee Fault. a) Vertical displacement. b) Horizontal displacement. From Williams et al. (submitted).

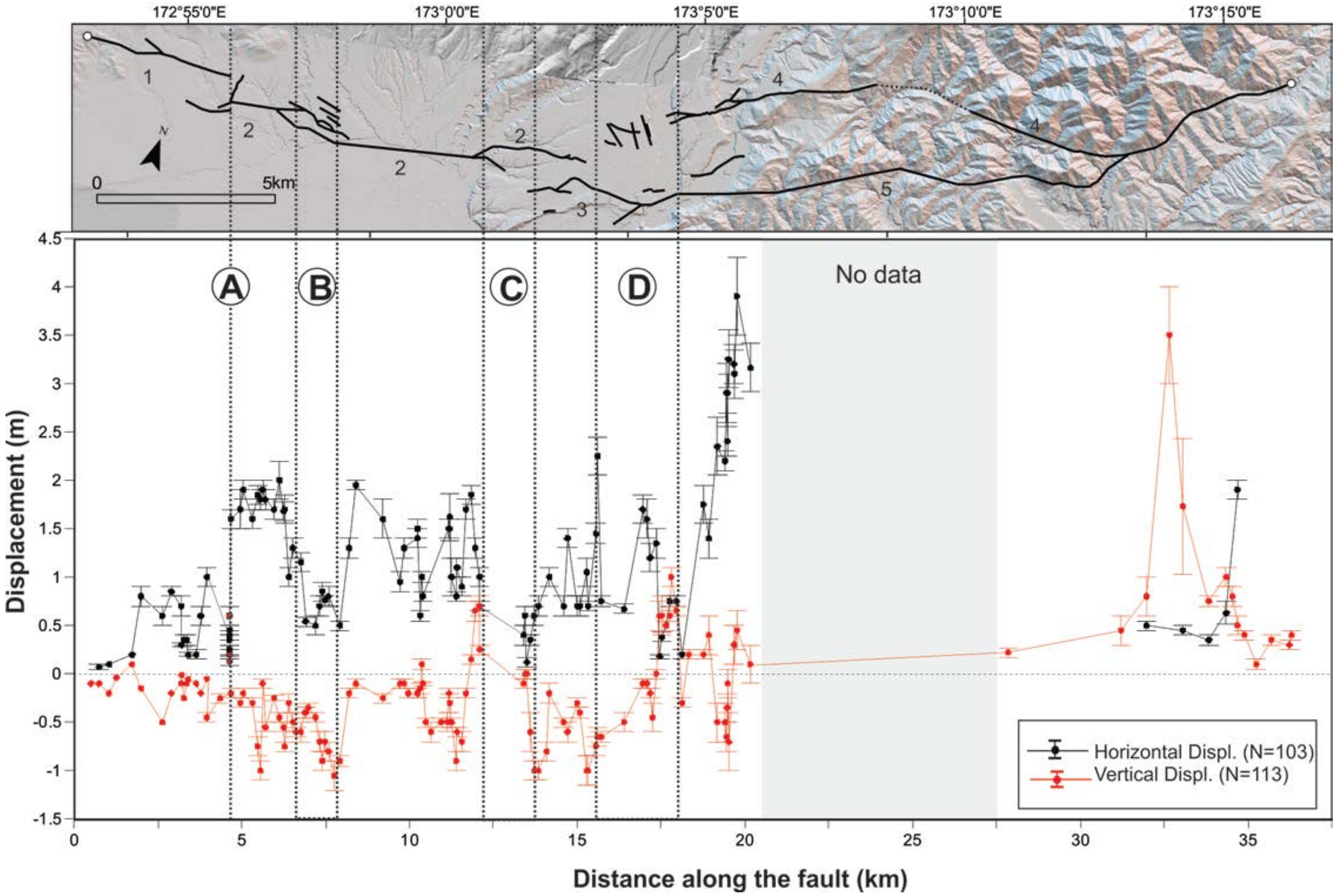

Figure 2.12 Map of The Humps Fault zone and vertical and horizontal slip distribution profiles. From Nicol et al. (submitted).

3.0 FAULT AND COASTAL DEFORMATION INVENTORIES

3.1 COASTAL DEFORMATION

The coastal deformation data is compiled in a GIS database and is described by Clark et al. (2017). This publication is open access and is currently linked to through the GeoNet website summary of the Kaikōura earthquake to promote public access. The complete high-resolution dataset of coastal deformation is available on request. This includes the LiDAR differencing measurements of coastal deformation at 1-m resolution along 90 km of coastline, and a summary Google Earth kmz file with deformation measurements every 250 m along the coastline.

3.2 GROUND-SURFACE FAULT RUPTURE MAPPING

The ground-surface fault rupture mapping and displacement measurements is also compiled in a GIS database, in a format compatible with entry into the New Zealand Active Faults Database (Langridge et al. 2016). The format is also suitable for future uses such as facilitating the mapping of fault avoidance zones for land use planning (Kerr et al. 2003).

A summary (1:250,000 scale) version is available for public download from the website https://data.gns.cri.nz/af/ and is described by Litchfield et al. (submitted). Between 1 July and 30 September 2017, this dataset has been downloaded 72 times.

The detailed (LiDAR scale) version can be made available upon request.

4.0 FUTURE WORK

4.1 COASTAL DEFORMATION

The Kaikōura Earthquake coastal deformation dataset is considered to be complete. We are aware of another team who undertook UAV flights over selected areas of the uplifted southern coast, who may yet document some more detailed coastal uplift measurements.

We have installed a survey network over part of the uplifted platform at Waipapa Bay to monitor changes to the platform with time. This will allow us to better understand evidence preserved from past earthquakes. We intend to re-survey this network at regular intervals (e.g., 6 monthly).

Another key next phase of work is to compare the Kaikōura Earthquake coastal deformation with past evidence from uplifted marine terraces. We have compiled some unpublished data in a GIS database and have undertaken some preliminary analysis (Litchfield et al. forthcoming; Clark et al. forthcoming). We then hope to undertake paleoseismological fieldwork (e.g., trenching) of the marine terraces to obtain high resolution deformation measurements and ages. As well as comparing with the Kaikōura coastal uplift data, the timing and magnitude of uplift events can be compared with the timing of paleoearthquakes and sense of movement on nearby faults. This will provide more information on the physical impact of past earthquakes as well as assessing the likelihood and extent of past multi-fault ruptures like the Kaikōura Earthquake.

4.2 GROUND-SURFACE FAULT RUPTURES

The ground-surface fault rupture dataset is considered to be mostly complete, but some further detailed fault mapping is still ongoing as part of student research projects. These projects include an MSc on the Kekerengu Fault, a PhD on the North Leader Fault, an MSc on the South Leader Fault, an MSc on the West Humps Fault Zone, a Professional Masters of Engineering Geology (PMEG) project on ground penetrating data over surface ruptures, and a PMEG study on landslides and the South Leader Fault.

Another major next phase of work is to undertake paleoseismological studies of the faults that have ruptured, as well as nearby major faults that didn't or had only minor rupture (e.g., the Hope Fault). This is important with regards to understanding whether the faults that ruptured in the Kaikōura Earthquake generally rupture together, or sometimes independently, or if there are other combinations of faults that could rupture together. All of these, as well as the recurrence intervals and time since the last earthquake have important implications for seismic hazard.

Much of the knowledge gained from the Kaikōura Earthquake also needs to feed into revisions of active fault earthquake source characterisation in the NSHM. Some of this work, as mentioned, has already started with the development of a Kaikōura Seismic Hazard model. Key issues to address are the better characterisation of multi-fault ruptures and incorporation of time dependent hazard.

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