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THE M_W7.8 2016 KAIKŌURA EARTHQUAKE: SURFACE FAULT RUPTURE AND SEISMIC HAZARD CONTEXT

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ABSTRACT

We provide a summary of the surface fault ruptures produced by the Mw7.8 14 November 2016 Kaikōura earthquake, including examples of damage to engineered structures, transportation networks and farming infrastructure produced by direct fault surface rupture displacement. We also provide an overview of the earthquake in the context of the earthquake source model and estimated ground motions from the current (2010) version of the National Seismic Hazard Model (NSHM) for New Zealand. A total of 21 faults ruptured along a c.180 km long zone during the earthquake, including some that were unknown prior to the event. The 2010 version of the NSHM had considered multi-fault ruptures in the Kaikōura area, but not to the degree observed in the earthquake. The number of faults involved a combination of known and unknown faults, a mix of complete and partial ruptures of the known faults, and the non-involvement of a major fault within the rupture zone (i.e. the Hope Fault) makes this rupture an unusually complex event by world standards. However, the strong ground motions of the earthquake are consistent with the high hazard of the Kaikōura area shown in maps produced from the NSHM.

INTRODUCTION

The Mw7.8 14 November 2016 Kaikōura earthquake was the latest in a series of damaging earthquakes to occur in the South Island of New Zealand over the past eight years. The earthquake was preceded by the Mw7.8, 2009 Dusky Sound and Mw7.1 2010 Darfield earthquakes, which ended a relatively quiescent period of approximately four decades with respect to large earthquakes in New Zealand [1,2]. In this paper we present an overview of the surface fault ruptures produced by the Kaikōura earthquake, and examples of the damage to buildings, transportation systems and productive farmland produced by direct ground surface fault rupture. An evaluation of the 2010 National Seismic Hazard Model (NSHM) [3] in the context of the earthquake is also presented. This paper provides a brief overview of the surface fault rupture characteristics of the earthquake. For a more comprehensive documentation of the surface ruptures, the reader is directed to [4] and [5]. The earthquake also caused tens of thousands of landslides, along with considerable liquefaction and shaking-related damage. These effects are covered in other papers within this special issue.

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The earthquake surface ruptures were mapped by a large team of scientists from New Zealand institutions and universities, and international groups (the author list of this paper). An initial helicopter reconnaissance was carried out by two scientists from GNS Science (co-authors Litchfield and Villamor), and through subsequent skype meetings several groups of scientists self-organised to map the various surface rupture areas. Helicopter reconnaissance as part of coseismic landslide mapping (particularly by coauthors Cox and Townsend), identified additional surface rupture targets for mapping. Scientists from the University of Canterbury, University of Otago, and GNS Science tackled the onshore surface ruptures south of Kaikōura, and scientists from GNS Science, Victoria University of Wellington, University of Auckland, and international groups mapped the onshore surface ruptures north of Kaikōura. Scientists from NIWA and GNS Science mapped seabed ruptures.

SEISMOTECTONIC SETTING

New Zealand's tectonic setting is characterised by two subduction systems that are linked by a zone of transpression in the South Island (Figure 1). In the North Island, the Pacific Plate subducts obliquely westward beneath the Australian Plate at the Hikurangi subduction margin, with relative plate motion of c.40 mm/yr at the latitude of Wellington [6]. In the South Island the majority of relative plate motion is taken up by dextral-oblique slip on the Marlborough Fault System (Figure 1b), and by dextral-oblique slip rates of 27+5 mm/yr on the Alpine Fault [7-11]. In the south of the country, eastward-directed subduction occurs beneath Fiordland on the Puysegur Subduction Zone. The Kaikōura earthquake occurred within a tectonically complex area of transition between the southern Hikurangi Subduction Zone and the oblique continental collision along the Alpine Fault. The Marlborough Fault System and North Canterbury fault and fold domain collectively mark this transition. The Kaikōura earthquake epicentre was located within the latter domain (Figure 1), and was approximately 80 km north of the Canterbury Earthquake Sequence epicentres of 2010-2011. However, the main energy release for the Kaikōura earthquake was near Kekerengu, within the Marlborough Fault System and about 100 km northeast of the earthquake epicentre [4,12].

The region surrounding the Kaikōura earthquake rupture has seen several large (Mw>7) earthquakes in the short (c.180 year) historical record of New Zealand [2]. The Mw7.4-7.7 1848 Marlborough earthquake ruptured the northeastern section of the Awatere Fault [13,14], followed by the Mw8.1-8.2 1855 Wairarapa earthquake [15,16]. Some time later, the Mw7.1 1888 Amuri earthquake ruptured the central (Hope River) segment of the Hope Fault [17,18] (see Figure 1) which was followed by the Mw7.1 1929 Arthurs Pass earthquake on the Poulter Fault [19], and much later by the Mw7.1 2010 Darfield earthquake [20]. In addition to these surface-rupturing earthquakes, the Cheviot 1901 and Motunau 1922 earthquakes were both shallow (<25 km depth) Mw 6.8 events in the North Canterbury region. Neither of the events produced observed surface rupture [2].

FAULT RUPTURES

The Mw7.8 Kaikōura earthquake was associated with a complex array of surface ruptures that involved at least 21 faults. Many were already mapped as active faults or geological faults prior to the earthquake, although some specific surface traces were previously unknown [21]. The earthquake ruptured the entire mapped lengths of some faults, and the partial lengths of others [5]. In the following, brief descriptions of the surface fault ruptures, sorted into the 13 geographic fault zones defined by the various mapping teams from southwest to northeast are provided (Figure 2). We also provide information on the recurrence intervals of causative active faults where known prior to the earthquake. Comment is also made as to whether the surface ruptures were included in the 2010 NSHM [3] - prior to the earthquake.

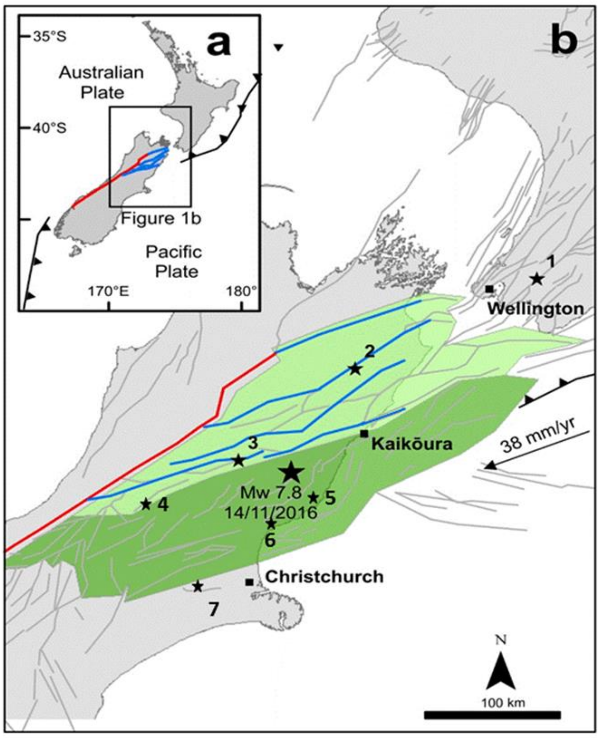

Figure 1: The plate tectonic setting of New Zealand (a), and of the northern South Island (b). On map (a) the boundary of the Pacific and Australian plates is expressed as a wide zone of transpression (translation and compression) through Marlborough and north Canterbury, and between the Hikurangi and Fiordland (Puysegur) Subduction Zones (the northeastern and southwestern thrust symbols, respectively; source Litchfield et al. submitted). The box in map (a) outlines the area shown in map (b). On map (b) the Kaikōura earthquake epicentre is shown by the large black star, and the epicentre locations of major historical earthquakes in central New Zealand are also shown as small stars and are numbered as follows: (1) Mw8.1-8.2 1855 Wairarapa earthquake; (2) Mw7.4-7.7 1848 Marlborough earthquake; (3) Mw7.1 1888 Amuri earthquake; (4) Mw7.1 1929 Arthurs Pass earthquake; (5) Mw6.8 1901 Cheviot earthquake; (6) Mw 6.8 1922 Motunau earthquake (locations from [1]), and; (7) Mw7.1 2010 Darfield earthquake. The two shades of green show the two tectonic regions bisected by the Kaikōura earthquake surface rupture (Marlborough Fault System to the north, and the North Canterbury fault/fold domain to the south). The most major faults of the Marlborough Fault System are shown as blue lines (combination of longest fault lengths and fastest slip rates), and are from north to south: Wairau; Awatere; Clarence, and; Hope faults. The Alpine Fault is also shown as a red line, and other active faults are shown as grey lines. The relative plate motion rate at the latitude of North Canterbury is shown on the right of the map (38 mm/yr). The relative plate motion vector is after [6], and the faults are from [10]).

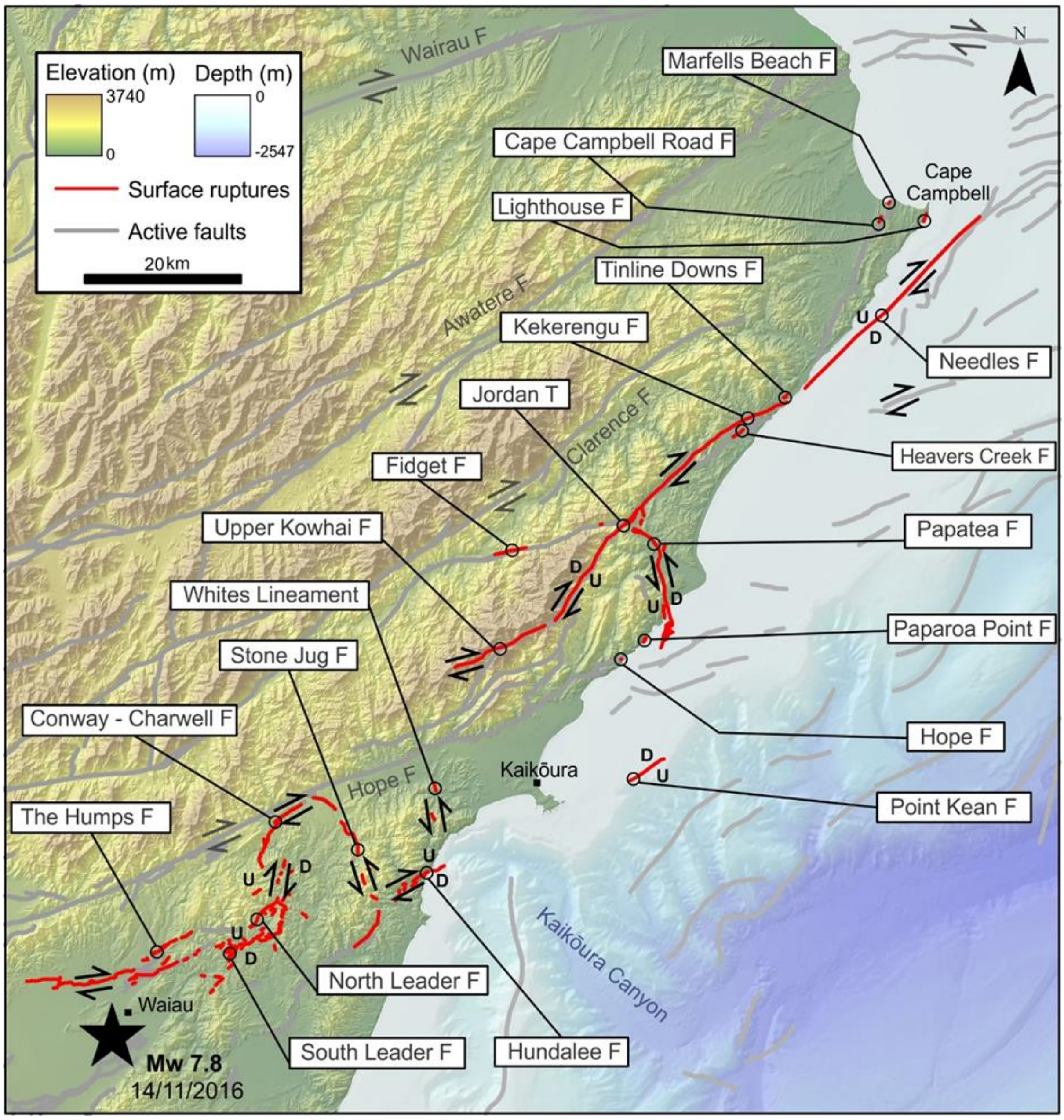

Figure 2: The surface fault ruptures of the Mw7.8 2016 Kaikōura earthquake. Grey lines show the active faults of the region (from the New Zealand Active Faults Database; [21]), and the surface ruptures resulting from the earthquake are shown as red lines. The geographic name assigned to each fault rupture zone is also shown. Source of map is Litchfield et al. [5].

The Humps Fault

This is a c.30 km long, east-northeast striking fault zone that produced dextral displacements of c.2 m and lesser vertical displacements (reverse, north side up). The surface rupture was close to the epicentre of the earthquake (Figure 2), and was undoubtedly responsible for the strong shaking and associated damage in the township of Waiau near the epicentre (Figure 2). A 5 km long zone of pre-existing traces had been identified on The Humps Fault prior to the earthquake [22], and a recurrence interval of 13,000±8710 years was assigned to the fault [23]. The fault is not explicitly represented in the 2010 NSHM, and the 2016 rupture length was much longer than the previously mapped active traces. The surface ruptures were mapped by the University of Canterbury authors, two of the GNS Science authors (Cox and Townsend), and one of the University of Otago authors of this paper (Toy).

North and South Leader Faults

These comprise a c.27 km long, north-striking zone of discontinuous 2016 rupture traces that links to the northeastern end of The Humps Fault (Figure 2). The North Leader Fault in turn links to the western end of the Conway-Charwell Fault. Dextral-reverse displacements of up to c.5 m were observed along the North Leader Fault surface rupture ([5]; Figure 2). The various splays associated with the North Leader Fault include a range of observed displacements, including dextral, sinistral, reverse (north side up) and normal, with oblique slip most frequently observed. The North Leader Fault ruptured across moderate to steep rugged terrain, and the continuity of the rupture traces was considerably disrupted by numerous large landslides. The South Leader Fault also comprises multiple splays, with predominant sinistral to dip slip-reverse senses of displacement. Maximum offsets reported are c.3.3 m sinistral and c.2.5 m vertical. The North and South Leader Faults were unknown prior to the earthquake, and hence are not incorporated into the 2010 NSHM. The ruptures were mapped by the University of Canterbury authors of this paper, aided by aerial reconnaissance by GNS Science.

Conway-Charwell Fault

This is a c.4 km long, northeast-striking rupture parallel and close to the southeast side of the Hope Fault (Figure 2). The fault dips steeply towards the northwest. Displacements of up to c.1.7 m (dominantly reverse, and with subordinate dextral slip) occurred during the earthquake [5]. The fault was mapped prior to the earthquake, and has an estimated recurrence interval of ≥6,000 years [23]. The fault was not included as an explicit source in the NSHM due to the short fault length and its closeness to the Hope-Conway fault source. The ruptures were mapped by the University of Canterbury authors, and two of the GNS Science authors (Cox and Townsend).

Stone Jug Fault

A c.17 km long, south to south-southeast striking fault rupture that intersects the northeast end of the Conway-Charwell Fault. Displacements of c.0.7 m were dominantly sinistral. The Stone Jug Fault was only known at the very northern end of the 2016 surface ruptures [22,23], and it was not included in the 2010 NSHM. The ruptures were mapped by authors from the Universities of Canterbury and Otago, GNS Science (Cox, Townsend, and Barrell), and NIED Japan.

Hundalee Fault

The earthquake ruptured a minimum of 12 km of the length of the onland northeastern section of the Hundalee Fault. The surface fault ruptures were observed within c.1.5 km of the south-southeastern end of the Stone Jug Fault. Maximum displacements of c.4 m dextral (with c.2 m reverse slip, north side up) were observed at the coast (Figure 2). Uplift of the shore platform north of the Hundalee Fault at the coast shows that the rupture also continued offshore, which is consistent with submarine investigations indicating c.2 km of surface rupture between the coast and the rim of the Kaikōura Canyon [24]. The Hundalee Fault was included in the 2010 NSHM [3]. The ruptures were mapped by University of Otago, GNS Science, and NIED Japan authors of this paper.

Whites Lineament

Two discontinuous rupture traces were observed along a less-than-14 km long zone between the coast in the south, and the Hope Fault to the north. Displacements were dominantly sinistral, and less than c.2 m. The fault was unknown prior to the earthquake, and therefore not included in the 2010 NSHM. These ruptures were mapped by way of helicopter reconnaissance (no landings possible) by University of Otago and GNS Science authors of this report.

Structure Offshore from Kaikōura Peninsula

Post-earthquake seafloor mapping has revealed a previously unidentified structure northeast of Kaikōura Peninsula, named the Point Kean Fault [5]. The mapping by NIWA authors of this paper is not complete, but a 2.1 km long, up to c.2 m high northeast-striking scarp (upthrown to the southeast) with suspected strike-slip displacement has been imaged. This structure was not a source in the 2010 NSHM. Despite the surface throw locally down to the northwest, dislocation modelling of a coincident reverse fault at a low dip to the northwest is required to match with the measured 2016 uplift of Kaikōura Peninsula, and also prehistoric Holocene shore platform uplifts [24,25]. The structure was not a source in the 2010 NSHM. The 2016 ruptures were mapped by the NIWA authors of this paper.

Upper Kowhai Fault

An up-to-17 km long, northeast-striking dominantly dextral surface rupture occurred during the earthquake, with maximum displacement of c.2 m. The fault was mapped prior to the earthquake [25,26]. It was not incorporated into the 2010 NSHM as it lies close to other major sources in the area (Hope-Conway, Jordan Thrust and Kekerengu fault sources; [3]). The ruptures were mapped by authors from GNS Science by helicopter reconnaissance (no landings were possible).

Jordan Thrust

Approximately 15 km of surface rupture occurred on the northern part of the Jordan Thrust, a northeast-striking fault that is located to the east of the Upper Kowhai Fault ([27]; Figure 2). Maximum dextral displacements of c.7 m, with subordinate vertical slip (east side up), occurred along the fault. The fault has an estimated recurrence interval for large earthquakes of 1,200 years [28], and it was included as part of a multi-fault source in the 2010 NSHM. The ruptures were mapped by a combination of authors from GNS Science, Victoria University of Wellington, and University of Auckland.

Papatea Fault

A c.19 km rupture occurred along this north-northwest striking fault, located close to the lower reaches of the Clarence River (Figure 2). Displacements of c.7 m (reverse, west side up, and sinistral, with approximately equal proportions of each) were observed along the fault. The fault rupture extended offshore in the south, and produced spectacular displacement and uplift of the wave-cut platform at the coast (Figure 2). The Papatea Fault had been mapped prior to the earthquake [22], but was not recognised as active. It was therefore not included as a fault source in the 2010 NSHM. The ruptures were mapped by a combination of authors from University of Auckland, GNS Science, and international institutions.

Fidget Fault

The central part of the fault produced surface ruptures of at least 3 km length, and dextral-oblique displacements of c.2 m were observed along two sections of the fault. The fault was mapped prior to the earthquake. Although no earthquake geology investigations have previously been carried out, Van Dissen et al. [29] assigned a recurrence interval in the range of 2,000-3,500 years. The fault was included as a source in the 2010 NSHM. The ruptures were mapped by authors from GNS Science.

Kekerengu Fault

Approximately 25 km of rupture occurred along the Kekerengu Fault, and the fault exhibited the largest displacements produced by the earthquake (c.11 m dextral [5]). The rupture intersected the Papatea Fault and Jordan Thrust in the southwest, and continued to the northeast and offshore (Figure 2). An earthquake geology trench excavated across the fault in 2016 by coauthors Little and Van Dissen was offset 9 m dextrally across the fault, which represents a “second” for trench investigations internationally (the first trench to be offset by a fault rupture was associated with the Mw7.3 1983 Borah Peak earthquake, Idaho [30]). A recurrence interval range of 380+30 years has been estimated for the fault [31,32], which was included as part of a multi-fault source in the 2010 NSHM. The ruptures were mapped by a combination of authors from Victoria University of Wellington, GNS Science, and international institutions.

Needles Fault

The rupture propagated offshore from the northeast end of the Kekerengu Fault potentially for 34 km (Figure 2), produced at least 3.5 m throw (west side up), and an unknown amount of dextral displacement. The coast marks the previously-defined boundary between the Kekerengu and Needles faults. The fault rupture is inferred to have terminated to the east of Cape Campbell, and close to the area of the 2013 Cook Strait and Grassmere earthquakes [33-35]. The fault had been mapped by NIWA prior to the earthquake [36], but the trace that ruptured had not been previously identified, and no data had been gathered to constrain the recurrence interval. The fault was included as part of a multi-fault source in the 2010 NSHM. The ruptures were mapped by authors from NIWA and GNS Science.

Other, minor ruptures were observed on faults near Cape Campbell, (LHF, MBF, and CCRF in Figure 2). These ruptures had lengths of 1 km or less, and showed displacements of 1.5 m or less. The Hope Fault also showed minor reverse-dextral slip on State Highway 1 at the coast, but the onshore sections of the fault otherwise did not show discernible rupture at the ground surface resulting from this earthquake.

FAULT DISPLACEMENT DAMAGE TO ENGINEERED STRUCTURES

The earthquake surface ruptures occurred through farmland and coastal areas where transportation, farming, fishing and tourism activities are located. While the surface ruptures did not pass through urbanised or industrial areas, they did affect some individual buildings on farms, and the earthquake impacts were regionally very significant. Furthermore, the significant length of the zone of surface ruptures (c.180 km) meant that impacts were very widespread. Many observations of damage to human-built structures by direct surface fault rupture were made. Displacement damage to State Highway 1 and the South Island Main Trunk Railway (SIMT) occurred both to the north and south of Kaikōura (on the Hundalee, Papatea and Kekerengu faults). Housing, farmland, and associated infrastructure were also impacted. In Table 1 we document the damage to infrastructure observed on the various surface fault rupture zones described in the previous section. We also show examples of direct fault displacement damage in Figures 3-13. While the majority of damage was due to strong ground motions and earthquake-induced landslides, we do not document these effects as they are covered in other papers in this special issue.

Figure 3: Oblique dip slip-dextral fault scarp of The Humps Fault at Glenbourne Farm that caused displacement damage to concrete slabs, farm tracks and fencing (Lat 42.615°S, Lon 173.105°E; view west; photograph by Jarg Pettinga).

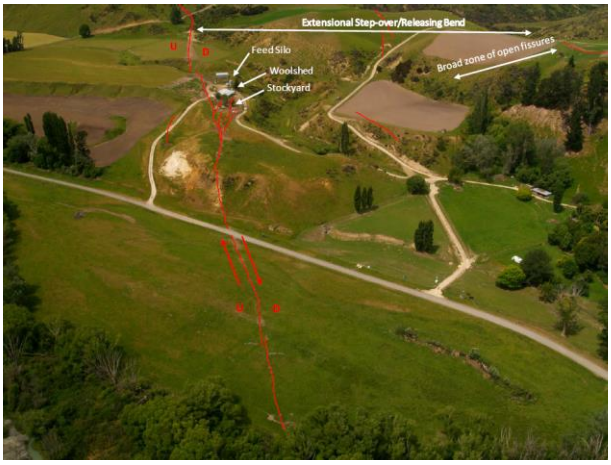

Figure 4: Aerial view of The Humps Fault surface rupture (red lines) at Glenbourne Farm, showing the sense of movement (red arrows) and highlighting farm infrastructure damaged by the earthquake (Lat 42.615°S, Lon 173.105°E; view northeast; photo and annotation by Clark Fenton).

Figure 5: Oblique transtensional rupture within The Humps Fault zone displacing State Highway 70 (the Inland Kaikōura Road; Lat 42.597°S, Lon 173.091°E; view towards the north; photograph by Jarg Pettinga).

Figure 6: The Humps Fault surface rupture through a farm worker's cottage at Hossack Downs (Lat 42.629°S, Lon 173.015°E; photograph by Jarg Pettinga).

Figure 7: Dextral-reverse displacement of the SIMT and State Highway 1 across the Hundalee Fault at Oaro (Lat 42.504°S, Lon 173.510 °E). The displacement of the road was sharp, but smoothing and resurfacing was just being completed when the photo was taken. The SIMT offset was diffused through embankment ballast and the flexibility of the rails, and in this view has yet to undergo any repair or modification (photograph by Mark Stirling).

Figure 8: Direct fault surface rupture of c.8 m (dextral) through a farm worker's house across the Kekerengu Fault (Lat 41.978°S, Lon 178.998°E; view to the west; photograph by Tim Little).

Figure 9: Aerial view of the area of the Kekerengu Fault rupture shown in Figure 8 (view to the north; photograph by Tim Little).

Figure 10: Rupture through farm buildings on a southwestern stand of the Papatea Fault near the coast (Lat 42.201°S, Lon 173.875°E; view to the south; photograph by Robert Zinke).

Figure 11: Surface fault rupture across a northeastern strand of the Papatea Fault near the coast deformed and distorted the SIMT line and severed the East Coast fibre optic cable at this location. Orange flagging marks the location where the fibre optic cable was cut by fault rupture and subsequently repaired (view to the southwest; photograph by Robert Zinke).

FAULT RUPTURES IN THE CONTEXT OF THE NSHM

The surface fault ruptures and associated strong ground motions of the Kaikōura earthquake occurred in an area of high seismic hazard within the zone of plate boundary deformation between the Pacific and Australian plates, as shown in Figure 14 and detailed in the 2010 NSHM [3]. Specifically, the 2010 NSHM-derived peak ground accelerations (PGAs) are in the range of 0.5-0.9 g for the 500 year return period, and over 1 g for the 2500 year return period (area inside circle in each map in Figure 14). These return periods encompass the range of return periods most commonly considered in engineering applications. The maximum PGA observed in the areas of the rupture was 1.3 g in the township of Ward [12], which is consistent with the greater-than-1 g NSHM-derived motions for the 2500 year return period in the area. This is because of the high density and relatively short recurrence intervals of fault sources in the 2010 NSHM in the Kaikōura area. Furthermore, the background seismicity component of the NSHM would also have contributed to the high hazard in Figure 14 due to the high instrumental seismicity rates in the area [3].

Figure 12: Aerial view of a southwestern strand of the Papatea Fault surface rupture across State Highway 1 and the SIMT line. This scene lies about 100 m south of that shown in Figure 10 and 900 m southwest of the Figure 11 view of the northeastern strand of the fault (view to the south; photograph from Chris Hayles).

Figure 13: Avulsion of the Clarence River onto farmland as a result of displacement along the Papatea Fault (Lat 42.115°S, Lon 173.844°E). The obvious distributary of the river to left of centre has occurred as a result of oblique-sinistral slip and formation of a zone of echelon folding and faulting (west side up) between the arrows and across the river (view to the northwest; photograph by Julie Rowland).

Table 1: Engineered structures impacted by surface rupture. These are divided up according to the faults with surface rupture.

Fault	Engineered structures impacted by surface rupture	Figure in this paper
Kekerengu	State Highway 1	
	Kekerengu Valley Road	Figure 9
	Wiffens Road	
	SIMT railway line	
	Main east coast fibre optic cable	
	Residential dwelling	Figures 8, 9
	Fence lines	
Papatea	State Highway 1	Figure 12
	Waipapa Road	
	Waiautoa Road	
	Clarence Valley Road and bridge	
	SIMT railway line	Figures 11, 12
	Main east coast fibre optic cable	Figure 11
	Several residential dwellings	Figure 10
	Fence lines	
Hundalee	State Highway 1	Figure 7
	Birches Road	
	SIMT railway line	Figure 7
	Deer fences	
The Humps	Leslie Hills Road	
	Hossack Downs Road	
	Sherwood Road	
	Inland Kaikōura Road (SH70)	
	Chaffeys Road	
	The Gates Road	
	Irrigation lines	
	Farm accommodation	Figure 6
	Stockyards	Figures 3, 4
	Fence lines	Figures 3, 4
	Woolsheds	Figure 4
	Barns	
	Feed silos	Figure 4
North and South Leader	Leader Road	
	Inland Kaikōura Road (SH70)	
	Irrigation lines	
	Farm accommodation	
	Stockyards	
	Fence lines	
	Woolsheds/barns	
Conway-Charwell & Stone Jug	Inland Road (SH70)	
	Cloudy Range Road	
	Stag & Spey Road	
	Fence lines	
	Stockyards	
	Barns	

One 2010 NSHM single-fault source and one multi-fault source ruptured in the earthquake, (Hundalee Fault and Jordan Thrust-Kekerengu-Needles sources, respectively; Figures 2 and 15). This shows that the complexity of the Kaikōura earthquake rupture was in-part anticipated in the 2010 NSHM. The magnitude of the Jordan Thrust-Kekerengu-Needles source is Mw7.6 in the 2010 NSHM [3], which is insignificantly less than the Mw7.8 of the Kaikōura earthquake when uncertainties in the magnitude estimates are considered (one-sigma uncertainties of magnitude are typically c.+0.2 units). Inclusion of multi-fault ruptures (Figure 15) in the 2010 NSHM was an attempt to account for the high slip rates observed on relatively short faults in the area (e.g. Kekerengu Fault [38]). Also, at the time of development of the 2010 NSHM, consideration of multi-fault ruptures was generally seen as appropriate treatment of source epistemic uncertainty, given the rupture complexity of overseas events such as the 1992 Landers and 2002 Denali earthquakes. The Kaikōura earthquake surface rupture justifies additional consideration of multi-fault rupture complexity in future NSHM developments. However, we also acknowledge that the likely recurrence interval of a Kaikōura-like earthquake will be very long, implying that such a source may not be a significant contributor to overall probabilistic seismic hazard. Specifically, Litchfield et al. [5] suggest that the recurrence interval of Kaikōura events will be at least as long as the longest recurrence interval of the individual faults or fault zones involved in the earthquake (The Humps Fault, 13,000±8710 years [23]).

Surface ruptures occurred on several faults that were not represented as sources in the pre-earthquake 2010 NSHM. These are The Humps, Leader, Charwell-Conway, Stone Jug, Whites Lineament, Upper Kowhai, Papatea, and Point Kean faults. These surface ruptures were associated with faults that were either: (a) previously unrecognised geologically and lacking surface expression due to steep vegetated terrain and/or slow slip rate (Leader, Stone Jug, and Whites Lineament); (b) were not characterised in the 2010 NSHM source model due to uncertainties of length and other parameters (The Humps and Charwell-Conway); (c) had not been considered to be active (Papatea), or; (d) had been considered as a part of other sources (Upper Kowhai). The background seismicity component of the NSHM was developed to provide estimates of the magnitude and recurrence of moderate-to-large earthquakes away from the defined fault sources, but at magnitudes considerably less than that of the Kaikōura earthquake (i.e. maximum background earthquake magnitude of Mw7.2).

The most surprising aspect of the Kaikōura earthquake is that the surface rupture zone straddled two tectonic domains and obliquely crossed the predominantly northeasterly grain of the Marlborough fault system (Figure 2). Furthermore, the earthquake did not trigger significant surface slip on the Hope Fault despite modelling by [4] inferring slip at depth, the fault being proximal to the fault ruptures. The Hope Fault has the second-fastest slip rate of New Zealand's active faults. Investigations on the eastern section of the fault indicate a slip rate of 23+4 mm/yr, and a recurrence interval of 180-310 years [25,28,39]. The Hope-Conway fault source (i.e. Conway sections of the Hope Fault) in the 2010 NSHM lies within a few km of the Conway-Charwell component of the 2016 Kaikōura surface ruptures. It is however possible that slip on the Conway-Charwell Fault was actually triggered by slip on the Hope Fault at depth. This part of the Hope Fault has a recurrence interval of 180-310 years [39], the most recent event constrained to have occurred in A.D. 1780+60 years (i.e. an elapsed time of 176-296 years since the last earthquake; [39]). The Hope-Conway section may therefore be at a stage of the earthquake cycle where it could easily have been involved in the Kaikōura earthquake.

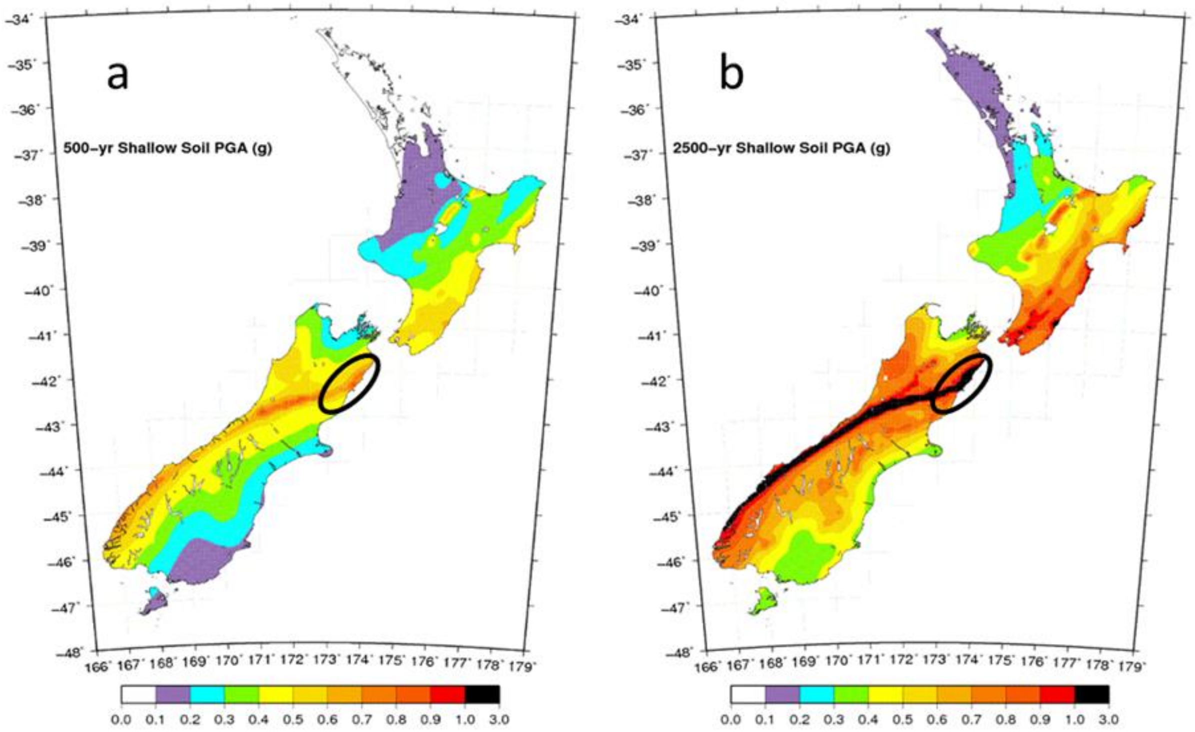

Figure 14: Maps produced from the 2010 NSHM [3] of the PGA (units of g) expected for: (a) 500, and; (b) 2500 year return periods, for shallow soil site conditions (Standards New Zealand [37]). The black ellipses define the area of the Kaikōura earthquake, and the high hazard inside the circles can be attributed to the high density of modelled fault sources and historical seismicity in the area of the earthquake.

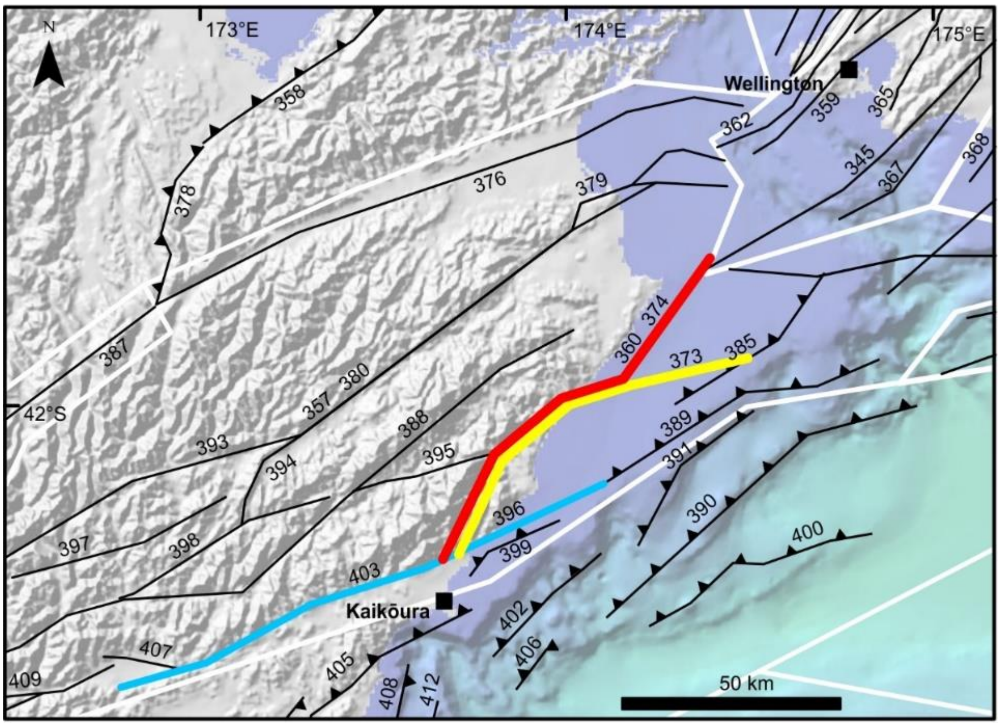

Figure 15: Fault sources of the 2010 NSHM [3] in the area of the Kaikōura earthquake (black lines with numbering according to the aforementioned reference). The 2016 rupture involved the following sources: Hundalee Fault (part; labelled 405); Fidget Fault (395) and a multi-fault combination (red line) involving the Jordan Thrust (in part), the Kekerengu Fault and the Needles Fault (labelled 360 and 374; Mw7.6). Other multi-fault sources defined in the NSHM are shown as a blue line (Hope-Conway-offshore; labelled 403 and 396; Mw7.7); and a yellow line (Jordan Thrust-Kekerengu-Chancet; labelled 373; Mw7.6). Base diagram after [3].

The above shows that the existing NSHM could benefit from further efforts to develop complex multi-fault ruptures additional to those considered thus far. The approach of defining hundreds of thousands of ruptures as in the UCERF3 model for California [40] would have likely come a little closer to anticipating the complexity of the Kaikōura earthquake. Investigation of the UCERF3 source modelling methods and underlying concepts is one of the areas of research that is likely to be conducted in future versions of the NSHM. Other avenues of research are expected to focus on the development of hybrid models that better account for the geometry and activity of unmapped fault sources than do the present background seismicity models.

SUMMARY AND CONCLUSIONS

We have provided a brief overview of the fault surface ruptures and related damage to engineered structures, transportation networks and farming infrastructure produced by the Mw7.8, 2016 Kaikōura earthquake. At least 21 faults ruptured the ground surface along a c.180 km long zone during the earthquake, including faults that were unknown prior to the event. The earthquake was notable for having ruptured in part obliquely across the northeast-striking Marlborough fault system. The earthquake is discussed in the context of the 2010 NSHM for New Zealand, which had considered multi-fault ruptures in the Kaikōura area, but not with the degree of complexity observed in the 2016 earthquake. The number of faults involved a combination of known and unknown active faults, a mix of complete and partial ruptures of known faults, and the non-involvement of the Hope Fault makes this rupture an unusually complex event. However, the area of the earthquake was adequately characterised as having high hazard in terms of probabilistic ground motions in the 2010 NSHM.

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