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The role of surface-rupturing faults in the Waiautoa microblock, Clarence valley, New Zealand, during the M_w 7.8 2016 Kaikōura Earthquake

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Abstract: *The M_w 7.8 Kaikōura Earthquake has presented an opportunity to study the scale of earthquake deformation from regional-scale, to individual block and micro-block tectonics. The 2.5 km^2 'Waiautoa microblock' refers to the high-angle fault intersection area between the co-seismic ruptures of the Jordan, Kekerengu, Papatea, and Waiautoa faults in the Clarence valley. Detailed field observations and post-earthquake LiDAR mapping indicate that these faults intersect in a complex, triangular fashion. The Jordan Thrust (dextral-normal in 2016) overlaps the dextral-reverse Kekerengu Fault near George Stream. In this same area, ruptures of the reverse-sinistral Papatea Fault almost intersect the Jordan Thrust. To close the triangle, the reverse-sinistral Waiautoa Fault is inferred to link the Papatea with the Kekerengu Fault. Assessment of piercing line markers indicates that co-seismic surface slip increases to the NE of George Stream, and is largely conserved along the length of the Waiautoa microblock as the Jordan, Kekerengu and Waiautoa faults share and exchange 7-9 m of surface slip. Summed co-seismic surface slip within the Waiautoa microblock is sub-equal to co-seismic surface slip on the Kekerengu Fault northeast of the microblock, suggesting that this zone of complexity promoted the continuation of surface rupture.*

Key words*: Waiautoa Fault, Papatea Fault, 2016 Kaikoura earthquake, transpression.*

INTRODUCTION

The 14 November 2016 (local time) M_w 7.8 Kaikōura earthquake, New Zealand is one of the largest, high-slip onshore earthquakes to have occurred in recent times (Hamling et al., 2017; Kaiser et al., 2017; Stirling et al., 2017). Surface rupture occurred on at least 14 named faults between Waiau in north Canterbury and offshore of Cape Campbell, Marlborough over c. 160 km (Fig. 1). The pattern of surface faulting is highly complex both at the full scale of the rupture and at smaller scales where individual faults or fault segments interact with adjoining faults. This paper documents an important complexity near the centre of the Kaikōura earthquake rupture zone where 5 distinct faults – the Jordan, Kekerengu, Papatea, Fidget and Waiautoa faults - join and overlap one another in three dimensions.

The Kaikōura earthquake occurred in the central part of the Australia-Pacific plate boundary through New Zealand in the northeastern South Island. This region is characterized by plate convergence rates of c. 37-40 mm/yr and a progression from compression in the southwest, to transpression and strike-slip motion in the northeast, across a transitional plate boundary setting where the leading edge of the Pacific plate subducts beneath the New Zealand margin (e.g. Wallace et al., 2012). Fault rupture during the Kaikōura earthquake began in the North Canterbury Domain and propagated into the Marlborough Fault System (MFS) (Litchfield et al., 2014; Langridge et al., 2016a) (Fig. 1). The vast majority of seismic energy and surface slip was released during the second half of the earthquake sequence when rupture of the northern faults within the MFS, initiated and propagated slip to the northeast (e.g. Kaiser et al., 2017).

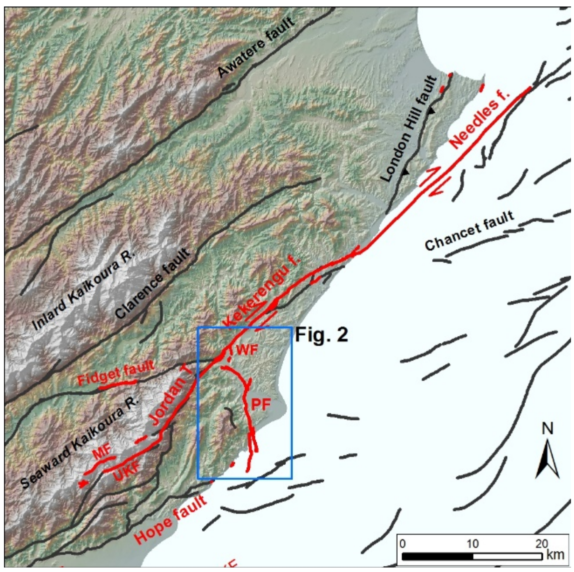

Figure 1: Map of the northern surface fault ruptures (red lines) in the 2016 M_w 7.8 Kaikōura Earthquake. Blue box indicates Fig. 2 highlighting the Papatea Fault (PF) and Waiautoa Fault (WF). See text for other abbreviations.

This paper describes the 'Waiautoa microblock' where five of the major northern faults join and overlap one another and where both proximity of individual fault ruptures and the partitioning of slip from one to another can be measured and documented. Understanding how faults and fault zones within the upper crust interact at the km-scale, with respect to the shape and size of fault stepovers and bends is of great relevance for considering the seismic hazard posed by integrated fault networks (Wesnousky, 2008; Barka and Kadinsky-Cade, 2002).

METHODOLOGY

Following the Kaikōura earthquake, we collected field observations where fault surface rupture was recognized and accessible, and undertook helicopter reconnaissance of sites in remote areas where landing was difficult or impractical. We employed a variety of techniques to measure surface slip including tape measure, sighting of scarp heights, real-time kinematic (RTK-GPS), total station, and UAV (drone) surveys. Offsets were recorded on cultural features including fencelines, roads, and planted treelines, and geomorphic features such as stream channels, risers and scree deposits. Due to the possibility of offsets being destroyed by bad weather and/or farm reparations and the slow availability of some airborne datasets, the faults were mapped and surveyed as quickly as was practical on the ground soon after the earthquake. In early 2017 we received aerial orththomosaics and in mid-2017 post-earthquake LiDAR coverage of most of the earthquake rupture zone. In some cases, such as along the coast and up the Clarence valley, pre-earthquake LiDAR surveys existed (Langridge et al., 2016b). In these cases, we developed Differential LiDAR (D-LiDAR) models of the ground surface change (Clark et al., 2017; Nissen et al., this volume). Field and GIS data were collated to produce surface rupture maps, slip vectors and slip distributions for individual faults (Jordan, Kekerengu, Papatea, Fidget and Waiautoa) within 10 km of the Waiautoa microblock area.

MAJOR FAULT RUPTURES ASSOCIATED WITH THE WAIAUTOA MICROBLOCK AREA

Papatea Fault - The Papatea Fault, which extends from offshore in Waipapa Bay to George Stream (Fig. 2), was recognised as an important NNW-striking bedrock, and possibly active, fault prior to the Kaikōura earthquake (Barrell, 2015; Rattenbury et al., 2006). Papatea fault ruptures have a variable strike along the mapped length of the fault. They are commonly reverse-sinistral in sense with a maximum (near-field) net slip of 7.4 ± 0.6 m. D-LiDAR profiles are consistent with InSAR results that suggest the Papatea Block (i.e. the block bounded by the Papatea, Jordan and Hope faults) moved vertically by 8-10 m (and by several m to the south) (Hamling et al., 2017). Offsets on the Papatea Fault are locally sinistral-reverse with up to 6 m of net slip at the coast across two distinct fault strands (Clark et al., 2017). Near the northern end of the fault, an impressive N-striking reverse-sinistral rupture scarp bends to the NW into a splaying, distributed zone of sinistral-normal faulting and monoclinal ruptures within the hangingwall. The main reverse-sinistral trace is progressively concealed in George Stream (Fig. 3).

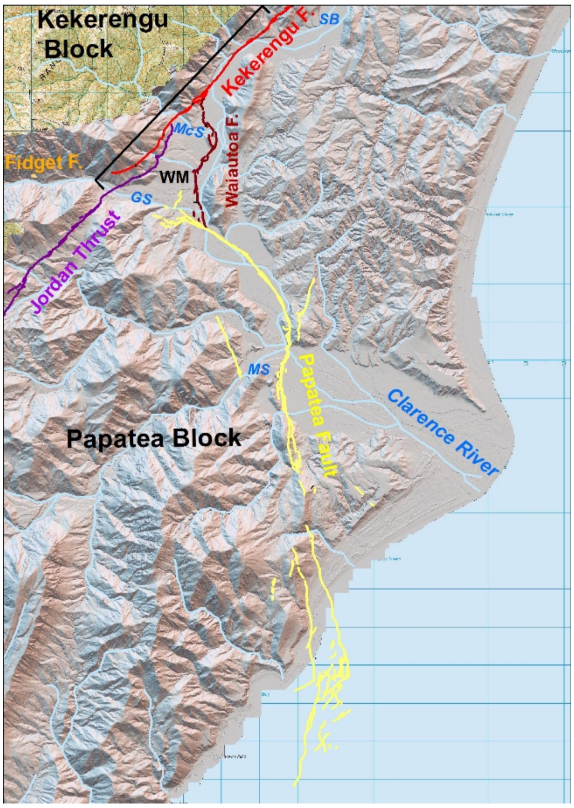

Figure 2: 2016 co-seismic surface rupture of the Papatea Fault (yellow) and ruptures of the Jordan (purple), Kekerengu (red) and Waiautoa (brick) faults in the vicinity of the Waiautoa microblock (WM). George (GS), Miller (MS) and Mclean (McS) streams and Shag Bend (SB) are labelled. Black line marks Fig. 4 slip-section.

Jordan Thrust - The Jordan Thrust is an important, northeast-striking, high-slip rate plate boundary fault that links the Kekerengu with the Hope Fault to the southwest (Van Dissen and Yeats, 1991). Following the earthquake, helicopter reconnaissance and limited ground observations indicated that only the northern half of this fault (as mapped) had surface rupture. Farther inland, parts of the Upper Kowhai Fault (UKF) and Manakau Fault (MF) within the Seaward Kaikōura Range also displayed surface rupture. The northern half of the Jordan Thrust typically displayed dextral-normal (uphill-facing) surface rupture with 3-4 m dextral slip near Miller Stream and up to 6-8 m at George Stream. Northeast of this point, the Jordan Thrust overlapped with rupture on the Kekerengu Fault. While dextral-normal motion was observed the long-term motion for this fault is of transpression, therefore, we entertain the possibility of a blind component of reverse motion on the Jordan fault.

Kekerengu Fault - The northeast-striking Kekerengu Fault represents the longest onland rupture (c. 28 km) and largest recorder of slip (up to 11.8 m dextral) during the Kaikōura earthquake sequence (Hamling et al., 2017; Stirling et al., 2017; Kearse et al., this volume). The southern half of the fault occurs from George Stream north along the Clarence River valley. Northeast of the river, the fault traverses farmland out to the Marlborough coast. While the highest offsets in 2016 were documented in the north, the southern half of the fault consistently produced surface ruptures with 9-11 m of dextral slip in the floor of the Clarence River and across the Shag Bend area. South of Shag Bend there is an apparent drop in the magnitude of slip toward Waiautoa Station and McLean Stream, where there is c. 6 m of dextral slip. South of McLean Stream, surface rupture associated with the Kekerengu Fault is dextral-normal in sense and coincides with pre-existing geomorphology within the rangefront (Fig. 3). Where it could be measured the slip between McLean Stream and George Stream decreased from c. 6 to 2 m and effectively to zero where the fault bends to the southwest to become the Fidget Fault.

Waiautoa Fault - The north-striking Waiautoa Fault is a short (3.4 km) reverse-sinistral slip fault that ruptured during the Kaikōura earthquake with slip up to c. 1 m. The presence of the Waiautoa Fault is coincident with the course of the Clarence River and Tertiary bedrock structure. In the north, the fault splays from the Kekerengu Fault and is characterized by reverse-slip rolls, thrusts and folds that generally follow pre-existing topography such as risers and alluvial fans. The fault proceeds south toward the Waiautoa homestead, where a reverse-slip rupture with 20-40 cm up-to-the-west motion is mapped across McLean stream in LiDAR images. The Waiautoa Fault is projected to the south according to the presence of surface ruptures and ridge-crest extension, toward the Clarence River bridge. Abutments of the bridge appear to be offset sinistrally by c. 1 m.

THE WAIAUTOA MICROBLOCK – INTERPRETATION

Careful mapping and surveying has allowed for the connection and correlation of the five mapped faults whose junction area form a 2.5 km^2 triangular area - the Waiautoa microblock. The Fidget Fault bends from an ENE to NE strike to merge with the Kekerengu Fault at the SW corner of the microblock. Minor to zero surface rupture slip on the Fidget Fault evolves abruptly into full surface rupture of the Kekerengu Fault with slip increasing from c. 6 to 10-12 m dextral in the northeast beyond the Waiautoa microblock. Multi-metre dextral slip on the Jordan Thrust reaches a peak at the southwestern end of the microblock at George Stream. To the north, rupture of the Jordan Thrust continues immediately east of, and overlapping with, the Kekerengu Fault, converging from an across-strike width of 350 m between surface ruptures to an observed minimum of <100 m (Fig. 3). In this overlap zone, there is a trade-off or sharing of fault slip between the Jordan and Kekerengu faults. For example, at the southern part of this overlap at George Knob a single long fenceline crosses both faults with 3.2 ± 0.4 m dextral slip on the former and 3.4 ± 0.4 m on the latter (Fig. 4). Toward the northern convergence of the Jordan-Kekerengu fault overlap, the Jordan Thrust appears more and more to be a thrust fault that partners the Kekerengu Fault.

The Papatea Fault almost certainly extends to the southwest corner of the Waiautoa microblock, though there is a lack of visible surface slip over c. 1.4 km between the northwest end of rupture on the Papatea Fault and the Jordan Thrust at George Stream. Similarly, despite a lack of continuous rupture or exposure, we infer that the Waiautoa Fault forms a link between the Kekerengu and Papatea faults and forms the eastern boundary of the Waiautoa microblock. The translation of slip off the Papatea Fault near its northern end and increased slip on the Kekerengu Fault north of Waiautoa Station both equate with a slip and kinematic transfer from these faults onto the Waiautoa Fault.

Figure 3: *View to the northeast at George Stream, which is impounded by dextral-normal slip on the Jordan Thrust, and cuts a swath through the native forest. The overlapping rupture of the Kekerengu Fault is upslope to the left of this photo.*

DISCUSSION

Observations

Mapping using a variety of tools indicates that the Waiautoa microblock forms a kinematic complexity at the southern end of the Jordan-Kekerengu-Needles rupture set within the 2016 Kaikōura earthquake sequence. This 2.5 km^2 fault junction area has accommodated the transpressional strain release of five distinct faults or fault segments in a single earthquake, dominated by dextral slip, but including reverse and sinistral motion. These five faults yield slip vectors consistent with the northeast to eastward kinematic motion across faults (relative to the coast and plate boundary). Rupture through this complexity (microblock) heralded the 2nd half of the complex Kaikōura earthquake sequence with the highest slips and strongest ground motions; thus the complexity did not act to inhibit rupture, rather it was central to a burst of fault ruptures, the timings of which can only be deduced from seismology (Kaiser et al., 2017; Duputel and Rivera, 2017). Simplified slip distributions (Fig. 4) indicate that 7-11 m of slip consistently passes into, or out of, the Waiautoa microblock area, thus either: 1) slip is: essentially conserved at a first order across the microblock, or 2) rupture energy (and therefore slip) grew out of the basin to reach a peak on the northern end of the Kekerengu Fault.

Implications

We can learn a lot about rupture process from 3rd order complexities involved in such complex earthquake ruptures. For example:

1) faults can join with hard or soft linkages in 3-D both in a mappable sense and in an individual earthquake rupture. The result of this is that it is important to map faults at the scale to which it is relevant, i.e. if a fault is being mapped for a critical facility or structure, such as a city, dam or nuclear facility, then the detail and the complexity that need to be considered are greater (e.g. Petersen et al., 2010). This paper highlights that because the Kaikōura ruptures have often been mapped at a scale of 1:1000, then far more complexity and a greater array of structures can be observed. This is also true for faults that can be mapped using airborne LiDAR and other digital datasets (e.g. Barth et al., 2012).

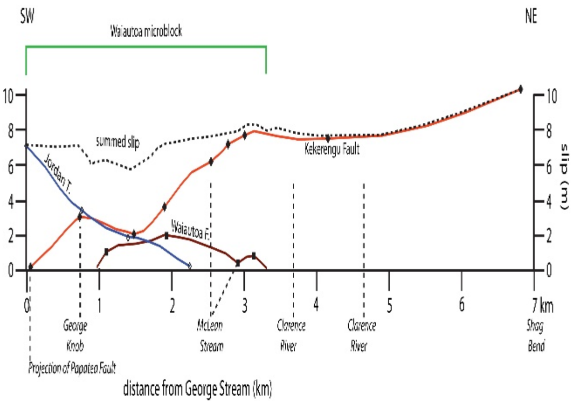

Figure 4: Simplified slip distribution across the Waiautoa microblock summing motion from the Jordan, Kekerengu and Waiautoa faults. Slip profile projected normal to Kekerengu Fault and includes dextral and reverse motion (see black line on Fig. 2).

2) faults can communicate in 3-D to effectively 'share' slip across a complexity. In the context of the Waiautoa Basin, the Jordan and Kekerengu faults overlap one another to share slip, while the Kekerengu and Papatea faults accommodate the complex transition from dextral-reverse to reverse-sinistral motion via the reverse-sinistral slip Waiautoa Fault.

3) small transpressive complexities such as the Waiautoa microblock may not be rupture inhibitors, but rather rupture promoters, or 'kickers'. Rupture of faults surrounding the Waiautoa microblock were involved in kicking off the 2nd half of the Kaikōura earthquake sequence. When such features are mapped for seismic source or hazard purposes they should not necessarily be considered as a structural complexity that will halt through-going fault rupture.

4) finally, along with the long histories of bedrock and geomorphic fault offsets on individual faults of the MFS (Freund, 1971), the Waiautoa microblock must be considered a long-lived geomorphic and kinematic feature as it is responsible for developing secondary topography and controls both the short term passage of the Clarence River, and its long-term history, sitting at the southern end of a 12 km deflection of this important river.

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