# Surface rupture and slip distribution of the Jordan-Kekerengu-Needles fault network during the 2016 Mw 7.8 Kaikoura earthquake, New Zealand.

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## Technical Abstract

During the 2016, $M_W$ 7.8 Kaikōura earthquake the Kekerengu fault ruptured the ground surface producing a maximum of ~12 m of net displacement (dextral-slip with minor reverse slip), one of the largest five co-seismic surface rupture displacements so far observed globally. This study presents the first combined onshore to offshore dataset of co-seismic ground-surface and vertical seabed displacements along a near-continuous ~83 km long strike-slip dominated earthquake surface rupture of large slip magnitude. Onshore on the Kekerengu, Jordan Thrust, Upper Kowhai and Manakau faults, we measured the displacement of 117 cultural and natural markers in the field and using airborne LiDAR data. Offshore on the dextral-reverse Needles fault, multibeam bathymetric and high-resolution seismic reflection data image a throw of the seabed of up to 3.5±0.2 m. Mean net slip on the total ~83 km rupture was 5.5±1 m, this is an unusually large mean slip for the rupture length compared to global strike-slip surface ruptures. Surveyed linear features that extend across the entire surface rupture zone show that it varies in width from 13 to 122 m. These cultural features also reveal the across-strike distribution of lateral displacement, 80% of which is, on average, concentrated within the central 43% of the rupture zone. Combining the near-field measurements of fault offset with published, far-field InSAR, continuous GPS and coastal deformation data, suggests partitioning of oblique plate convergence, with a significant portion of co-seismic contractional deformation (and uplift) being accommodated off-fault in the hanging-wall crust to the northwest of the main rupturing faults.

# Introduction

Measurement of co-seismic slip along surface fault ruptures following large magnitude earthquakes has, in recent decades, become routine practise. Empirical rupture parameters such as the length, magnitude and distribution of co-seismic surface displacements are key inputs into fault scaling relationships used in seismic hazard evaluations worldwide (e.g., Wells and Coppersmith, 1994; Stirling *et al*., 2013). Observations of surface ruptures in large-magnitude earthquakes are of particular importance because these events are relatively rare, they accommodate large displacements that typically dominate the long-term slip budget of a fault or faults, and they are capable of causing widespread damage. The study of co-seismic surface fault displacement has benefited recently from the application of remote sensing technology, such as interferometric synthetic aperture radar (InSAR) (e.g., Peltzer *et al*., 1998; Hamling *et al*., 2017) light detection and ranging (LiDAR) (e.g., Oskin *et al*., 2012) and high-resolution optical satellite image correlation (e.g., Zinke *et al*., 2014). Despite the ability of these techniques to characterize fault rupture deformation over wide regions, there remains no substitute for field-based investigation for characterizing the amount, style and distribution of on-fault deformation. This is especially true where the faulted region is criss-crossed by fence lines and other elongate once-straight markers that allow on-fault (and near-fault) deformation to be documented in detail (as is the case with the Kekerengu fault following the 2016 Kaikoura earthquake).

Our study documents the distribution of horizontal and vertical surface displacement along the ~83 km of near-continuous surface rupture during the $M_w$ 7.8 Kaikōura earthquake of the Manakau, Upper Kowhai, Jordan Thrust, Kekerengu and Needles faults. We document changes in slip with distance along strike and, in places, with distance perpendicular to the strike of the main surface rupture trace. This study presents the first combined onshore to offshore dataset of co-seismic ground-surface and vertical seabed displacements along a near-continuous strike-slip dominated earthquake surface rupture of large slip magnitude. Onshore analysis is based primarily on field surveys, and secondarily on analysis of airborne LiDAR topographic data and orthorectified aerial photographs. High-resolution bathymetric data and TOPAS seismic reflection profiles were used to image the seafloor trace and identify co-seismic throw along the Needles fault.

## Research Objectives

1) Determine the co-seismic surface slip distribution, rupture length and mean slip on the Jordan-Kekerengu-Needles fault network during the Kaikoura earthquake.

2) Produce detailed maps of ground surface rupture along the Jordan-Kekerengu-Needles fault network, documenting variations in width and geometry.

3) Determine the across-strike distribution of co-seismic surface slip at various points along the length of the Kekerengu fault rupture.

## Key Findings and Conclusions

***Objective 1)*** Through detailed mapping of ground surface and seabed rupture, we have determined that the Jordan – Kekerengu – Needles fault network ruptured in the 2016 Kaikoura earthquake along an ~83 km length. 53 km of onshore rupture extended from the Seaward Kaikoura Ranges in the southwest, to agricultural grassland near the coast at Kekerengu. Offshore on the Marlborough shelf, 30 – 35 km of seabed rupture was mapped on a newly-identified trace of the Needles fault.

Horizontal surface displacement measurements along the onshore section of the Jordan – Kekerengu – Needles fault network describe a semibell-shaped envelope of dextral slip (Fig. 1). The central ~10 km of this displacement profile contains the largest offsets (10 -12 m), and includes the largest measured surface displacement of ~12 m, one of the largest five co-seismic displacement observed worldwide (Fig. 1a). No suitable markers of horizontal displacement were available offshore on the Needles fault. Vertical offset data on the 27 km-long Kekerengu fault averaged 1.5 m, locally exceeded 2 m and showed mostly up-to-the-northwest, reverse displacement. In contrast, on the Jordan Thrust and Upper Kowhai faults, vertical displacement was exclusively up-to-the-southeast and normal. From the northeast edge of the Seaward Kaikoura ranges to the southwestern rupture tip, vertical displacement magnitudes tapered from ~3 m to 0 m over a distance of ~ 30 km. Offshore on the Needles fault, vertical offsets were mostly up-to-the-northwest with an average magnitude of 2 m.

Combining both our horizontal and vertical displacement data and offshore uncertainties, we calculated a net slip for the Jordan – Kekerengu – Needles fault network. When integrated along the 83 km length of the rupture, a mean value of 5.5 m of net slip was determined. This is unusually large when compared to other strike-slip earthquake surface ruptures around the world. We suggest that the large average displacement in this earthquake may be due to a deeply-penetrating rupture, one that extends down to depths of 20-25 km. This inference is supported by the elastic dislocation modelling of Hamling et al (2017) and Clark et al (2017), who use Satellite Radar, GPS and coastal deformation data to constrain co-seismic slip at depth on the Jordan – Kekerengu – Needles fault network.

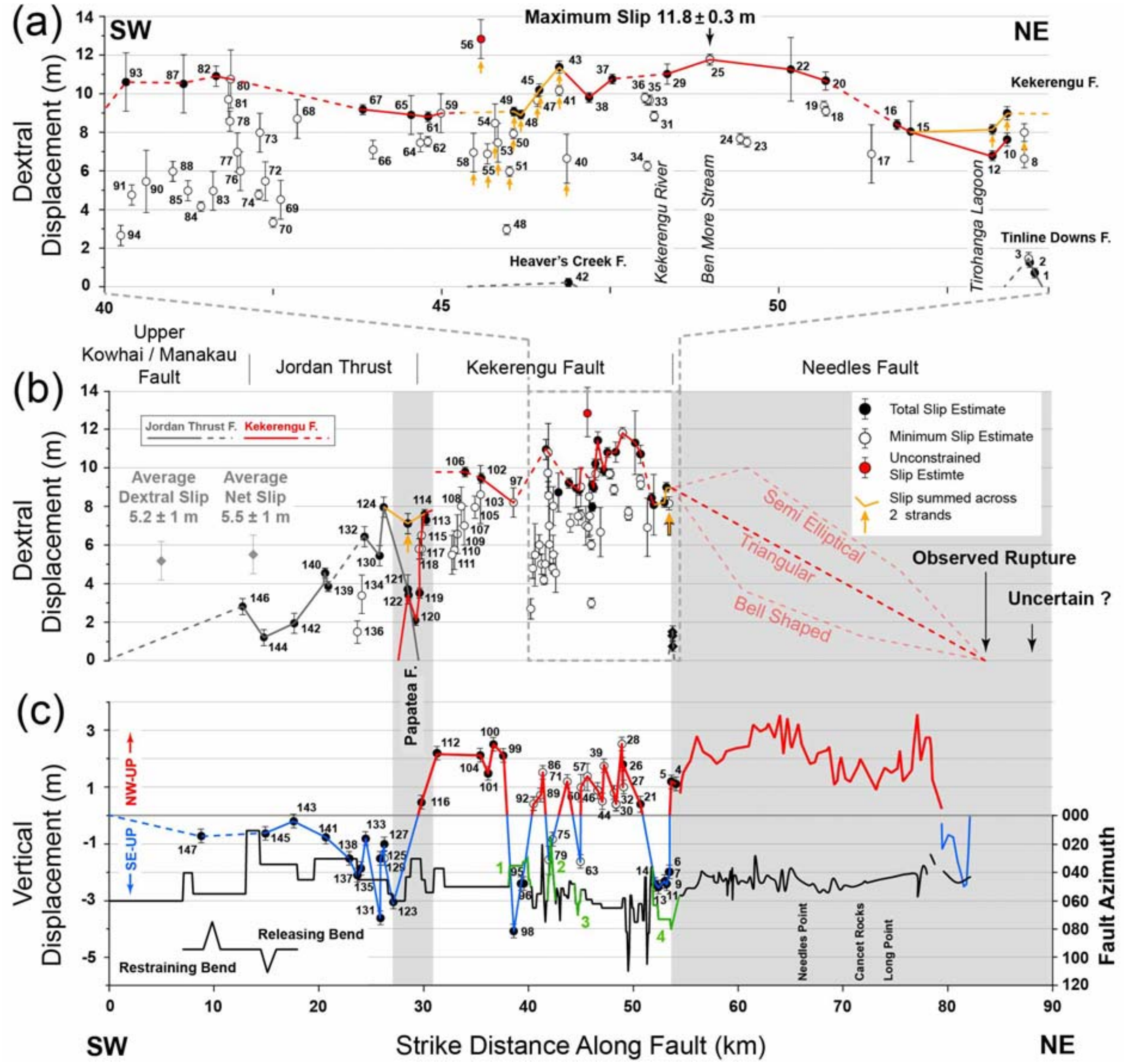


**Figure 1. Distribution of dextral and vertical surface-rupture displacement along the Upper Kowhai, Jordan Thrust, Kekerengu and Needles faults resulting from the 2016 Kaikoura earthquake. For full explanation the reader is referred to Kearse et al (2018).**

***Objective 2)*** Detailed maps (scales up to 1:3000) of ground surface rupture along 53 km of the onshore Jordan – Kekerengu – Needles fault network were produced, and were based upon field investigation and interpretation of post-earthquake, LiDAR-derived topographic data. These maps highlight the large variation in structural complexity and width along this stretch of 2016 surface rupture. Widths of discrete ground surface rupture (as opposed to widths of co-seismic displacement zones) vary between 5 – 300 m, with the larger values typically associated with bends in the rupture trace.

***Objective 3)*** The distribution of co-seismic dextral displacement in an across-strike direction was determined at 14 sites on the Kekerengu fault, where long, previously-straight fence lines extended across (and beyond) the rupture zone. We found that dextral slip (~8 – 12 m) at these sites was distributed within a zone between 13 – 122 m wide. On average, 80% of the total dextral displacement was focused within the central 43% of the rupture zone. Moreover, significant percentages of the total dextral displacement (in one extreme case >90%) were accommodated outside of the zone of discrete ground rupture (which was typically between 5 – 30 m). In addition to these data, we also undertook a cadastral (i.e., before and after the earthquake) survey of a network of fence posts that surround two sites on the Kekerengu fault, and which spanned up to 700 m across strike. The results of this survey showed that 10% of additional, distributed dextral slip occurred beyond the reach of the ~150 m-long fence lines, at distances of up to 260 m from the rupture trace. Such strains may not be recorded in the geomorphic record, and thus may not be encoded within Single Event Displacement (SED) and slip rate estimates derived from restored geomorphic piercing points across narrow fault zone widths (<50 m). These types of measurements will potentially systematically underestimate the total surface displacement across faults and therefore underestimate long-term slip rates.

# Impact

Large-magnitude earthquakes pose a significant hazard to New Zealand. To quantify the hazard associated with these large events, our current seismic hazard model uses empirical data—such as historic earthquake surface rupture lengths, surface slip distributions and earthquake magnitudes—to develop fault scaling regressions (e.g., Stirling et al., 2013). However the sample size of these empirical datasets are currently small, and suffer from a significant lack of observations of large-magnitude, surface rupturing earthquakes. When these rare events do occur, it is therefore crucial—from a seismic hazard perspective—to learn everything we can from them, in order to better inform our hazard forecast. This study provides a key step towards infilling this gap in observational data, by documenting the surface rupture length and distribution of surface displacements resulting from a Mw 7.8 earthquake.

To avoid damages associated with direct surface fault rupture deformation (i.e., permanent ground displacement, as opposed to shaking-related damages) in New Zealand, care is taken when developing on or near to active faults. The width of active fault avoidance, termed "fault avoidance zones" are determined on a case-by-case basis and are informed by detailed geomorphological mapping around an active fault trace, with the purpose of ensuring a level of life safety (Kerr et al., 2004). As these recommendations are based upon the recognition of paleo surface ruptures expressed in the landscape, they will not take into account any distributed ground deformation too subtle to be recorded in the geomorphic record. Such deformation was however, identified by this study, following the 2016 Kaikoura earthquake. Although the small ground strains associated with this peripheral deformation would likely not induce building collapse, they may still be of consideration where damage avoidance, and not just collapse avoidance is paramount.


## Acknowledgements

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## Links to published research

For a comprehensive account of this study the reader is referred to the following article:


*Kearse, J., T. A. Little, R. J. Van Dissen, P. Barnes, R. Langridge, J. Mountjoy, W. Ries, P. Villamor, K. Clark, A. Benson, G. Lamarche, M. Hill, and M. Hemphill-Haley (2018) Onshore to Offshore Ground-Surface and Seabed Rupture of the Jordan-Kekerengu-Needles Fault Network During the 2016, $M_w$ 7.8 Kaikoura Earthquake, New Zealand, Bull. Seismol. Soc. Am. Special Issue of the Kaikoura Earthquake, doi: 10.1785/0120170304*

This article can be accessed via the following website (last accessed 19/06/2018):

[https://pubs.geoscienceworld.org/ssa/bssa/article/530021/onshore-to-offshore-ground-surface-and-seabed](https://pubs.geoscienceworld.org/ssa/bssa/article/530021/onshore-to-offshore-ground-surface-and-seabed)

# References


*Clark, K. J., E. K. Nissen, J. D. Howarth, I. J. Hamling, J. J. Mountjoy,W. F. Ries, K. Jones, S. Goldstien, U. A. Cochran, P. Villamor, et al. (2017). Highly variable coastal deformation in the 2016 Mw 7.8 Kaikōura earthquake reflects rupture complexity along a transpressional plate boundary, Earth Planet. Sci. Lett. 474, 334–344.*

*Hamling, I. J., S. Hreinsdóttir, K. Clark, J. Elliott, C. Liang, E. Fielding, N. Litchfield, P. Villamor, L. Wallace, T. J. Wright, et al. (2017). Complexmultifault rupture during the 2016Mw 7.8 Kaikōura earthquake, New Zealand, Science 356, no. 6334, doi: 10.1126/science.aam7194.*

*Kerr, J., S. Nathan, R. Van Dissen, P. Webb, D. Brunsdon, and A. King (2004). Planning for development of land on or close to active faults: A guideline to assist resource management planners in New Zealand, Ministry for the Environment ME Number 565, 67 pp.*

*Oskin, M. E., J. R. Arrowsmith, A. H. Corona, A. J. Elliott, J. M. Fletcher, E. J. Fielding, P. O. Gold, J. Javier Gonzalez Garcia, K.W. Hudnut, J. Liu- Zeng, et al. (2012). Near-field deformation from the ElMayor–Cucapah earthquake revealed by differential LIDAR, Science 335, 702–705.*

*Peltzer, G., P. Rosen, F. Rogez, and K. Hudnut (1998). Poroelastic rebound along the Landers 1992 earthquake surface rupture, J. Geophys. Res. 103, 30,131–30,145.*

*Stirling, M., T. Goded, K. Berryman, and N. Litchfield (2013). Selection of earthquake scaling relationships for seismic-hazard analysis, Bull. Seismol. Soc. Am. 103, 2993–3011.*

*Wells, D. L., and K. J. Coppersmith (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, Bull. Seismol. Soc. Am. 84, 974–1002.*

*Zinke, R., J. Hollingsworth, and J. F. Dolan (2014). Surface slip and off-fault deformation patterns in the 2013 Mw 7.7 Balochistan, Pakistan earthquake: Implications for controls on the distribution of nearsurface coseismic slip, Geochem. Geophys. Geosys. 15, 5034–5050.*