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Greendale Fault rupture of 2010 (Darfield Earthquake, New Zealand): an Example of Recurrence Interval and Ground-surface Displacement Characterisation for Land-use Planning and Engineering Design Purposes

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ABSTRACT

The ground surface rupture of the Greendale Fault generated by the 2010 M_w 7.1 Darfield earthquake, New Zealand, is one of the best documented surface ruptures worldwide. This detailed documentation has allowed the formulation of design curves for characterising distributed strike-slip surface fault rupture displacement that have utility in developing mitigation strategies aimed at reducing damage to engineered structures caused by surface fault rupture. Paleoearthquake trenching and OSL dating along the central portion of the fault indicate that the penultimate surface rupture probably occurred ~20,000–30,000 years ago, implying average recurrence intervals ranging from ~10,000 to 60,000 years. In accord with the Ministry for the Environment "Active Fault" guidelines, we recommend re-classifying the Greendale Fault as Recurrence Interval Class V (10,000–20,000 years), compared to the previous estimation of Class IV (5000–10,000 years). This reclassification implies that more permissive land-use would be appropriate across the fault deformation zone.

Introduction

The M_w 7.1 Darfield earthquake of 4 September, 2010, had a shallow focus (~11 km deep), and an epicentre about 40 km west of the Christchurch city centre (Fig. 1). It was a complex event, involving rupture of multiple fault planes with most of the earthquake's energy release resulting from slip on the previously unrecognized Greendale Fault (e.g., Gledhill et al. 2011; Beavan et al. 2012). Greendale Fault rupture propagated to the ground surface and directly impacted, and damaged, numerous engineered structures such as single-storey buildings, roads and power lines (Van Dissen et al. 2011; Quigley et al. 2012).

Ground deformation can contribute significantly to losses in major earthquakes. Compared to areas affected only by strong ground shaking during an earthquake, those areas that also suffer permanent ground deformation (e.g., liquefaction, slope failure, surface fault rupture) sustain greater levels of damage and loss. This relationship was clearly demonstrated during the 2010-2011 Canterbury earthquakes (e.g., NZSEE 2010, 2011; EQ Spectra 2014). Ultimately, the mitigation of the risks posed by these ground deformation hazards depends on the integrated application of appropriate engineering design and risk-based land-use policy (e.g., Bray 2001; Kerr et al. 2003; Saunders & Beban 2012; Oettle & Bray 2013). The

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success of such approaches depends upon an accurate characterisation of the ground deformation hazards.

In this paper, we quantify Greendale Fault surface rupture deformation both along-strike and perpendicular to strike. We also present dating results that constrain the timing of the penultimate surface rupture earthquake on the Greendale Fault, from which we estimate an average recurrence interval for the fault. We use these characterisations to place Greendale Fault surface rupture into a wider hazard context that, we hope by example, will facilitate the future mitigation of surface fault rupture hazard in New Zealand and elsewhere.

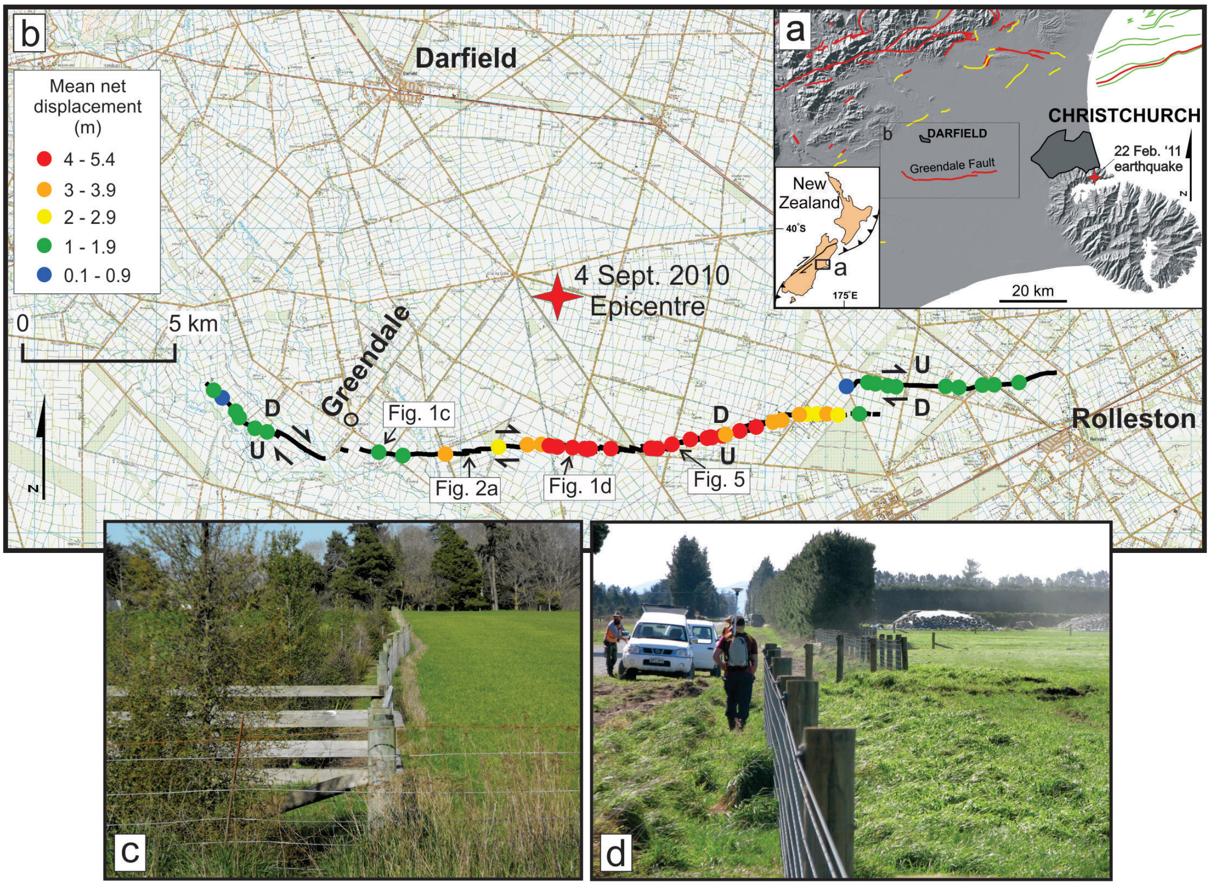

Figure 1. a) General location of the Greendale Fault and other tectonically active structures. Red lines are active faults, and yellow and green lines are, respectively, onland and offshore active folds. b) Mapped surface trace of the Greendale Fault (black line) and measured surface rupture displacements (coloured dots). c) Fence line adjacent to Coaltrack Road right-laterally offset by ~1.7 m across an ~100 m wide surface rupture deformation zone. d) Fence line near Courtenay Road right-laterally offset by ~4.3 m across an ~35 m wide deformation zone.

Characterisation of Surface Rupture Displacement

The Greendale Fault surface rupture extended for ~30 km across a low-relief alluvial plain with pastoral farming land-use, and comprised a distinctive series of *en echelon*, east-west striking, left-stepping traces (Figs. 1 & 2a) (Quigley et al. 2012). Many fences, roads and crop-rows were displaced dextrally across the surface rupture deformation (Figs. 1c & 1d) and provided ideal markers for measuring the amounts and patterns of deformation

(Litchfield et al. 2013). Dextral strike-slip is primarily accommodated by horizontal flexure with subordinate slip on discrete shears, and averaged 2.5 m with a maximum of 5.2 m. There was minor vertical deformation generally comprising decimetre-amplitude bulging, locally reaching 1 to 1.5 m at fault bends. Perpendicular to fault strike, surface rupture displacement was distributed across an ~30 to 300 m wide deformation zone; the width of the deformation zone was greatest at step-overs, and damaging ground strains developed within these. On average, 50% of the horizontal displacement occurred over 40% of the total width of the deformation zone with offset on observable shears typically accounting for less than about a third of total displacement. Where the overall horizontal deformation was less than ~1 to 1.5 m, there were few if any discrete ground cracks and shears. The distributed nature of Greendale Fault surface deformation reflects the up-to-several hundred-metre thick Quaternary gravel deposits underling this sector of the Canterbury Plains (Jongens et al. 2012).

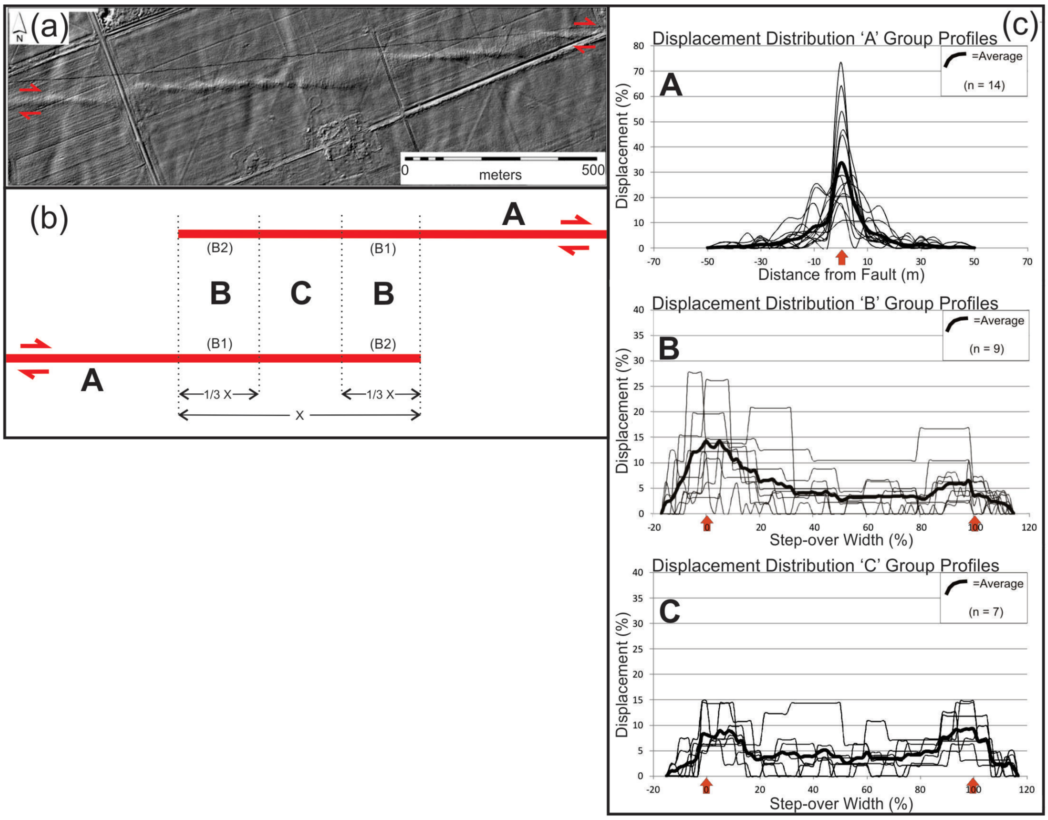

Figure 2: a) Lidar hillshade image showing distinctive pattern of side-stepping traces along a 1.5 km-long portion of the Greendale Fault. b) Conceptual structural positions on a fault step-over; A is where the fault comprises a single trace, B represents the start/end of a step-over, and C represents the middle of a step-over. c) Displacement distribution plots, and their averages, of dextral deformation profiles across the Greendale Fault grouped according to the fault trace structural positions, A, B & C, defined in Figure 2b.

We further characterised the variations in surface rupture deformation zone width by grouping, and plotting, the 30 deformation profiles that cross the entire fault zone according to their structural position on the fault trace (Fig. 2) (Van Dissen et al. 2013). In these plots, all deformation profiles are normalised to displacement, and for those profiles crossing a step-over, they are also normalized to step-over width. All three structural groupings (A, B & C of Fig. 2c) show that horizontal deformation was predominantly distributed, rather than concentrated solely on a small number of discrete shears. Even where the fault comprises a single trace (group A of Fig. 2) significant distributed deformation occurs over a width of ~30 to 40 m. Across the central part of a step-over (group C), dextral deformation is distributed and equally shared across both sides of the step-over. At the beginnings/endings of a step-over (group B) deformation is, again, distributed, with the dominant side of the step-over (B1 of Fig. 2b) typically carrying about two to three times more displacement than the subordinate side (B2 of Fig. 2b).

Figure 3a plots the Greendale Fault's average displacement distributions for the three structural groupings (A, B & C) defined in Figure 2, along with their corresponding cumulative displacement curves. Figure 3b shows analogous plots for a hypothetical strike-slip case where deformation is entirely discrete. Figure 3c combines these plots onto a single diagram. Comparable displacement plots are available for two sites along the 1906 rupture of the San Andreas Fault (Bray & Kelson 2006) and 11 sites along the 1999 ruptures of the North Anatolian Fault (Rockwell et al. 2002). Invariably, those strike-slip displacements were less distributed than the Greendale displacement, more distributed than the hypothetical discrete case, and would fall between the two "bounding" curves of Figure 3c. We suggest that Figure 3 has relevance as a first-approximation design curve to aid in engineering and land-use applications where it is desirable to characterise the manner in which strike-slip surface fault rupture deformation is distributed perpendicular to fault strike. See Van Dissen et al. (2013) for more detail, and Kelson et al. (2004) and Hitchcock et al. (2008) for related examples.

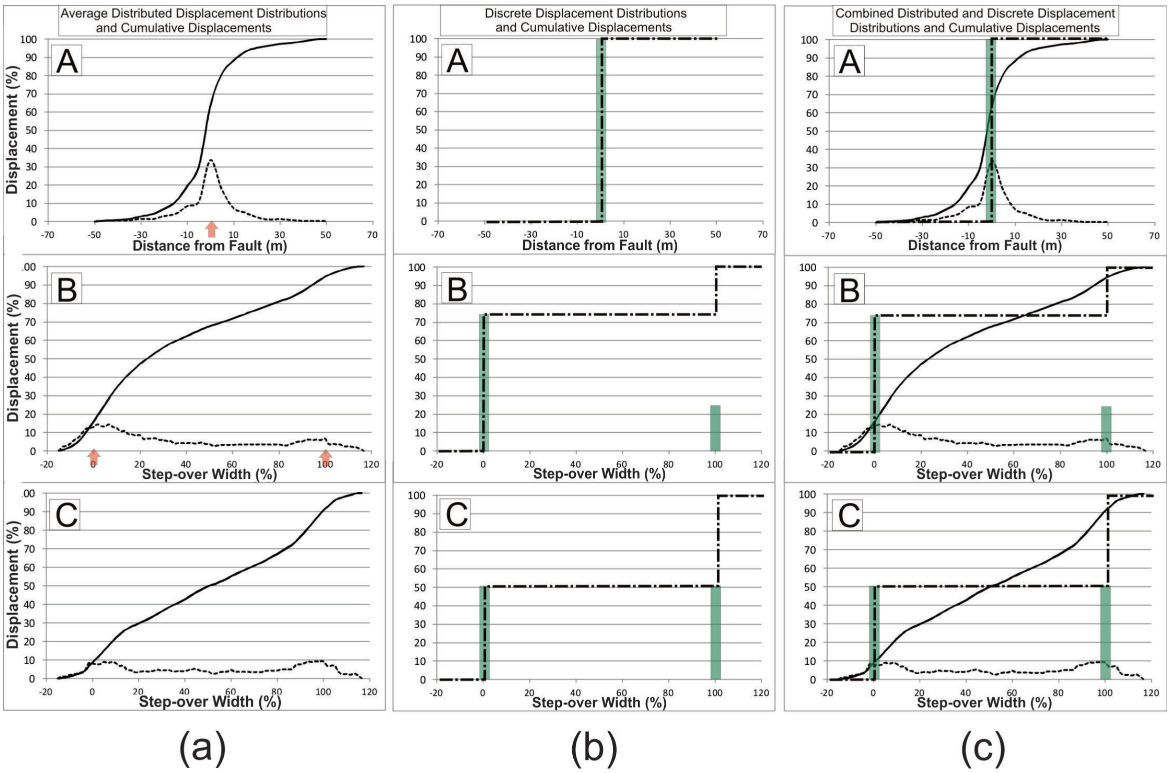

Figure 3: a) Average displacement distributions (dotted lines) and cumulative displacement curves (solid lines) for the Greendale Fault for the three fault trace structural groupings - A, B & C - defined in Figure 2. b) Displacement distributions (green shaded bars) and cumulative displacement curves (dot-dash lines) for a hypothetical case where strike-slip deformation is entirely discrete. c) Figures 3a & 3b combined, highlighting the differences in slip distribution between the hypothetical end-member discrete displacement example, and the near end-member distributed displacement (Greendale) example.

Timing of Past Surface Rupture

The Canterbury earthquake sequence delineated a number of previously unrecognised active faults, but the recurrence intervals on these faults remain largely unresolved. To illuminate the recurrence interval question for the Greendale Fault, two paleoearthquake trenches were excavated across the central portion of the fault (Hornblow et al. 2014a, 2014b). The results of one of these trenches are summarised below.

At the Highfield Road trench site (Fig. 4) discrete surface fracturing accommodated ~30% of the total ~4.8 m of right-lateral displacement; the remainder was accommodated by distributed deformation spread over ~175 m width. The trench itself was excavated across the maximum horizontal displacement gradient within the surface rupture deformation zone; it was ~30 m long by 3 m deep, and spanned ~65% of total horizontal deformation at the site. Most of the surface fractures exposed in the trench were undetectable in the gravel-dominated alluvial deposits at depths ≥ 1 m below the ground surface; however, large (>5 m long), discrete Riedel shears continue to depths exceeding 3 m (i.e., the base of the trench), and clearly displace interbedded gravels and thin sand-filled paleo-channels. One of the distinct Riedel shears at the Highfield site, R3 (Fig. 4), displaced linear surface features (e.g., fences, roads and plough lines) and a subsurface (0.6 m deep) paleo-channel by 60 cm right-laterally and 10 cm vertically, indicating that the paleo-channel has been displaced only in the Darfield earthquake.

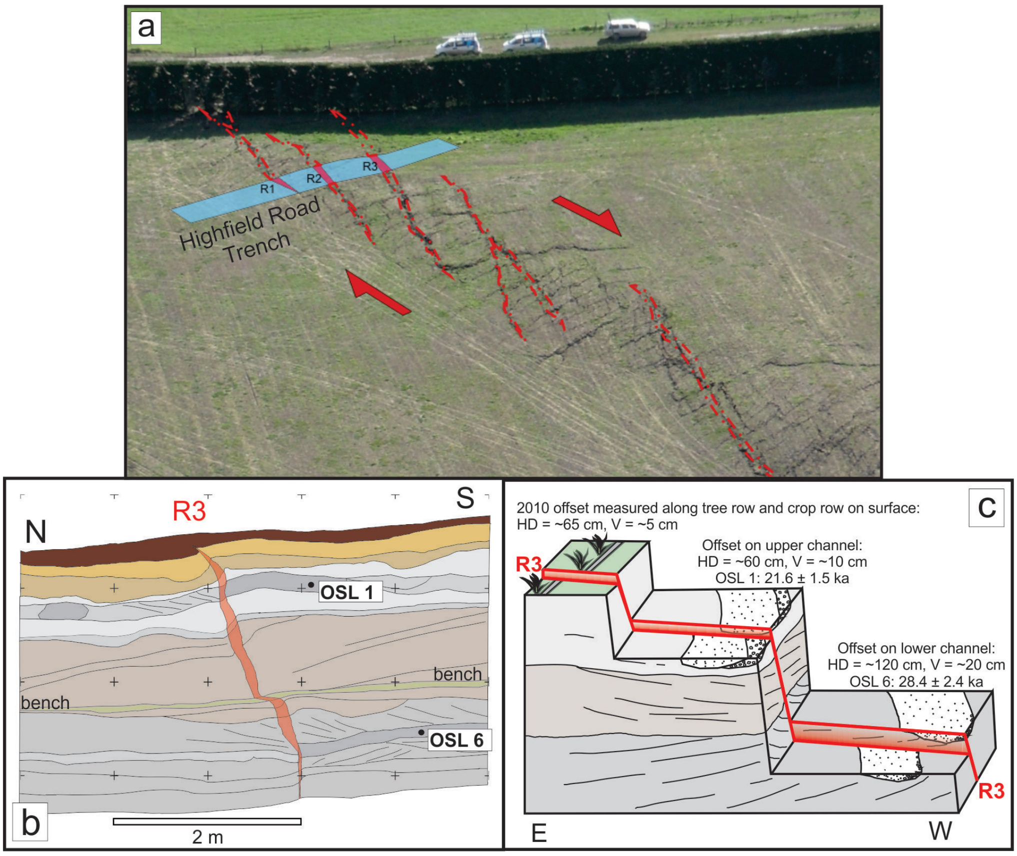

Figure 4: a) Oblique aerial view northwest across the Highfield Road trench site with distinct Riedel shears highlighted in red. b) Log of the east wall of the trench showing the R3 Riedel shear, and locations of OSL samples 1 & 6. Units exposed in trench were predominantly loose gravel-dominated alluvial deposits. c) Schematic diagram showing displaced paleo-channels across the R3 Riedel shear. HD and V denote horizontal and vertical displacement, respectively.

Optically stimulated luminescence (OSL) dating of the paleo-channel yielded an age of 21.6 ± 1.5 ka (1 ka = 1000 years ago). Two additional paleo-channels at ~2.5 m depth with OSL ages of 28.4 ± 2.4 ka and 33 ± 2 ka have been displaced ~120 cm right-laterally and ~20 cm vertically. The doubling of displacement at depth is interpreted to indicate that the Greendale Fault penultimate surface-rupturing event at this location occurred between ~ 20 and 30 ka.

Greendale Fault Recurrence Interval Classification and Fault Avoidance Zones

In the aftermath of the Darfield earthquake, and in response to re-build pressures in areas near the Greendale Fault, the Canterbury Regional Council commissioned an investigation to map and zone the Greendale Fault (Villamor et al. 2011, 2012) in accord with the New Zealand Ministry for the Environment's best-practice guidelines on planning for development of land on, or near, active faults (Kerr et al. 2003), hereafter referred to as the MfE Guidelines. In the MfE Guidelines, the surface rupture hazard of an active fault is characterised by two parameters: 1) the location/complexity of surface rupture of the fault (i.e. the mapping of Fault Avoidance Zones), and 2) the activity of the fault, as measured by its average recurrence interval of surface rupture (i.e. the characterisation of Recurrence Interval Class). Figure 5 presents examples of the Fault Avoidance Zone mapping of Villamor et al. (2011, 2012) for the Greendale Fault. The Fault Avoidance Zones are attributed as *well defined*, *distributed*, and *uncertain*, and range in width from about 70 m to greater than 300 m. The MfE Guidelines promulgate a risk-based approach to land-use planning, and recommend that more restrictive Resource Consent Categories be applied to *well defined* Fault Avoidance Zones, and more permissive Resource Consent Categories be applied to *uncertain* Fault Avoidance Zones.

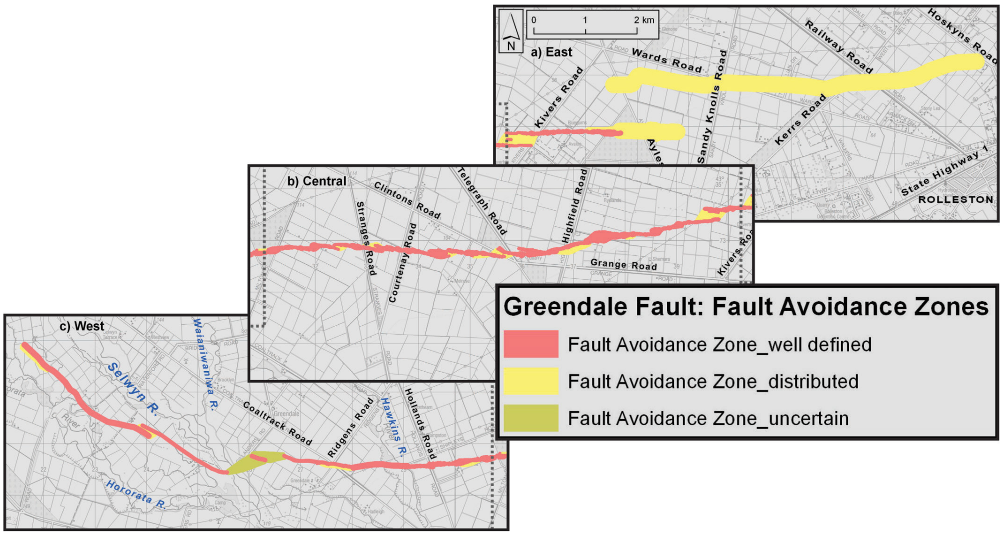

Figure 5: Fault Avoidance Zones for the Greendale Fault.

With regards to Recurrence Interval Class (RIC), the single Greendale Fault surface rupture inter-event time of 20–30 kyr (1 kyr = 1000 years) can be used to estimate an indicative range of "permissible" average recurrence intervals for the fault by making the following assumptions:

1. Average recurrence interval has a lognormal distribution. Lognormal is a commonly used distribution for average recurrence interval (e.g., Nishenko & Buland 1987; Rhoades et al. 1994). For the Greendale Fault this implies that the one inter-event time of 20–30 kyr is part of the lognormal distributions about "permissible" average recurrence intervals.
2. Coefficient of variation (CoV) of average recurrence interval ranges from 0.4 to 0.8. See Dawson et al. (2008) and Nicol et al. (2012) for data and analyses that support this choice of CoV range.
3. The minimum "permissible" average recurrence interval (aveRImin) is within plus one standard deviation of the inter-event time, and the maximum "permissible" average recurrence interval (aveRImax) is within minus one standard deviation of the inter-event time, such that:

   $$ln(aveRImin) + \sigma = ln(IET), \text{ and } ln(aveRImax) - \sigma = ln(IET) \quad (1)$$

   where σ is the standard deviation, $\sigma = (ln(CoV^2 + 1))^{½}$, and *IET* is inter-event time.

Solving for minimum "permissible" average recurrence interval (aveRImin) and maximum "permissible" average recurrence interval (aveRImax) yields ~10 kyr and ~60 kyr, respectively. In other words, by this approach, the one Greendale Fault inter-event time of 20–30 kyr is compatible with average recurrence intervals that range between ~10 kyr and ~60 kyr.

Villamor et al. (2011) provisionally characterised the Greendale Fault as RIC IV (5000 to 10,000 years), but noted that the RIC was poorly constrained, and that additional paleoearthquake data from the fault would be desirable. The paleoearthquake information obtained by Hornblow et al. (2014a, b), and resulting estimates of average recurrence interval in the range of ~10 kyr to ~60 kyr, suggests that the Greendale Fault should be re-classified as being Recurrence Interval Class V (10,000 to 20,000 years). It is possible that the fault has a recurrence interval greater than 20,000 years, but acknowledging the assumptions made in the recurrence interval derivations, we consider that a conservative classification of RIC V is appropriate. This reclassification implies that more permissive land-use would be appropriate across the fault deformation zone.

Discussion & Conclusions

The Canterbury earthquake sequence has been New Zealand's most costly natural hazard event, with estimated losses upwards of $40 billion (equivalent to ~30% real GDP). This debilitatingly large loss illustrates a clear economic and societal need in New Zealand to improve earthquake resilience. This would necessitate progress to be made on a number of related fronts, particularly in regard to improved levels of damage limitation and post-event functionality in the built environment, and greater sustainability in land-use. Related to this is the realisation that as performance expectations increase for an engineered structure, then increased characterisations of the hazards that may impact that structure are also required so that the risks posed by those hazards can be more fully accommodated in the design, construction and siting of the structure.

We consider that the ground-surface fault rupture characterisations presented here for the Greendale Fault, and related characterisations for active faults elsewhere, will continue to advance the engineering and geotechnical communities' ability to parameterise and define future surface fault rupture hazard. Improved parameterisation of surface fault rupture hazard, especially when combined with rupture resilient design concepts and land-use planning guidance, will facilitate development of successful mitigation strategies aimed at reducing the damage caused by surface fault rupture, and improving the post-event functionality of structures that may be impacted by fault rupture.

References

Beavan J, et al. Fault slip models of the 2010–2011 Canterbury, New Zealand, earthquakes from geodetic data and observations of postseismic ground deformation. *New Zealand Journal of Geology and Geophysics* 2012; **55**: 207-221.

Bray JD. Developing mitigation measures for the hazards associated with earthquake surface fault rupture. Proceedings, *A Workshop on Seismic Fault-Induced Failures – Possible Remedies for Damage to Urban Facilities 2001*, Japan Society for the Promotion of Science, Tokyo, Japan: 55-79. 2001.

Bray JD, Kelson KI. Observations of surface fault rupture from the 1906 earthquake in the context of current practice. *Earthquake Spectra* 2006; **22**: S69-S89.

Dawson TE, et al. *Recurrence interval and event age data for Type A faults, Appendix B in The Uniform California Earthquake Rupture Forcast, version 2 (UCERF 2)*: U.S. Geological Survey Open-File Report 2007-1437B and California Geological Survey Special Report 203B: 48 p, 2008.

EQ Spectra. Special Issue: 2010-2011 Canterbury earthquake sequence. *Earthquake Spectra* 2014; **30**: 1-605.

Gledhill K, et al. The Darfield (Canterbury, New Zealand) M_w 7.1 earthquake of September 2010: a preliminary seismological report. *Seismological Research Letters* 2011; **82**: 378-386.

Hitchcock C, et al. Fault-rupture hazard characterization: applications of Paleoseismic trenching for detailed mitigation design. *Geotechnical Earthquake Engineering and Soil Dynamics* 2008; **IV**: 1-12.

Hornblow S, et al. *Paleoseismology of the 2010 M_w 7.1 Darfield (Canterbury) earthquake source, Greendale Fault, New Zealand*. GNS Science Report 2014-26: 27 p. 2014a.

Hornblow S, et al. *Paleoseismology of the 2010 M_w 7.1 Darfield (Canterbury) earthquake source, Greendale Fault, New Zealand.* Tectonophysics 2014b. http://dx.doi.org/10.1016/j.tecto.2014.10.004.

Jongens R, et al. Faulting and folding beneath the Canterbury Plains identified prior to the 2010 emergence of the Greendale Fault. *New Zealand Journal of Geology and Geophysics* 2012; **55**: 169-176.

Kelson KI, et al. Fault rupture assessment for high-pressure pipelines in the southern San Francisco Bay area, California. *Proceedings, International Pipe Conference,* Calgary, Canada. Paper IPC2004-212: 8 p. 2004.

Kerr J, et al. *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 p. 2003.

Litchfield N, et al. *Detailed analysis of Greendale Fault ground surface rupture displacements and geometries*. GNS Science Report 2013/18. 2013.

Nicol A, et al. *Variability in slip/event and recurrence intervals for large magnitude paleoearthquakes on New Zealand's active faults*. GNS Science Report 2012/41: 57p. 2012.

Nishenko SP, Buland R. A generic recurrence interval distribution for earthquake forecasting. *Bulletin of the Seismological Society of America* 1987; 77**:** 1382-1399.

NZSEE. Special Issue: Preliminary observations of the September 2010 Darfield (Canterbury) earthquake sequence. *Bulletin of the New Zealand Society for Earthquake Engineering* 2010; **43**: 215-439.

NZSEE. Special Issue: Effects of the 22 February 2011 Christchurch earthquake and its aftershocks. *Bulletin of the New Zealand Society for Earthquake Engineering* 2011; **44**: 181-430.

Oettle N, Bray J. Geotechnical mitigation strategies for earthquake surface fault rupture. *Journal of Geotechnical and Geoenvironmental Engineering* 2013; **139**: 1864–1874.

Quigley M, et al. Surface rupture during the 2010 M_w 7.1 Darfield (Canterbury) earthquake: Implications for fault rupture dynamics and seismic-hazard analysis. *Geology* 2012; **40**: 55-58.

Rhoades DA, et al. On the handling of uncertainties in estimating the hazard of rupture on a fault segment. *Journal of Geophysical Research* 1994; **99** (B7): 13,701-13,712.

Rockwell TK, et al. Lateral offsets on surveyed cultural features *resulting from the 1999 Izmut and Duzce earthquakes, Turkey.* Bulletin of the Seismological Society of America 2002; **92**: 79-94.

Saunders WSA, Beban JS. *Putting R(isk) in the RMA: technical Advisory Group recommendations on the Resource Management Act 1991 and implications for natural hazards planning*. GNS Miscellaneous Series 48: 57 p. 2012.

Van Dissen R, et al. Surface rupture displacement on the Greendale Fault during the M_w 7.1 Darfield (Canterbury) earthquake, New Zealand, and its impact on man-made structures. *Proceedings, 9th Pacific Conference on Earthquake Engineering*, Auckland, New Zealand. Paper 186: 8 p. 2011.

Van Dissen R, et al. Towards the development of design curves for characterising distributed strike-slip surface fault rupture displacement: an example from the 4 September, 2010, Greendale Fault rupture, New Zealand. *Proceedings, 19th NZGS Geotechnical Symposium*, Queenstown, New Zealand: 455-462. 2013.

Villamor P, et al. *Greendale Fault: investigation of surface rupture characteristics for fault avoidance zonation*. GNS Science Consultancy Report 2011/121: 52 p. 2011.

Villamor P, et al. Map of the 2010 Greendale Fault surface rupture, Canterbury, New Zealand: application to land use planning. *New Zealand Journal of Geology and Geophysics* 2012; **55**: 223-230.