SURFACE RUPTURE OF THE GREENDALE FAULT DURING THE DARFIELD (CANTERBURY) EARTHQUAKE, NEW ZEALAND: INITIAL FINDINGS

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SUMMARY

The M_w 7.1 Darfield (Canterbury) earthquake of 4 September 2010 (NZST) was the first earthquake in New Zealand to produce ground-surface fault rupture since the 1987 Edgecumbe earthquake. Surface rupture of the previously unrecognised Greendale Fault during the Darfield earthquake extends for at least 29.5 km and comprises an en echelon series of east-west striking, left-stepping traces. Displacement is predominantly dextral strike-slip, averaging ~2.5 m, with maxima of ~5 m along the central part of the rupture. Maximum vertical displacement is ~1.5 m, but generally < 0.75 m. The south side of the fault has been uplifted relative to the north for ~80% of the rupture length, except at the eastern end where the north side is up. The zone of surface rupture deformation ranges in width from ~30 to 300 m, and comprises discrete shears, localised bulges and, primarily, horizontal dextral flexure. At least a dozen buildings were affected by surface rupture, but none collapsed, largely because most of the buildings were relatively flexible and robust timber-framed structures and because deformation was distributed over tens to hundreds of metres width. Many linear features, such as roads, fences, power lines, and irrigation ditches were offset or deformed by fault rupture, providing markers for accurate determinations of displacement.

INTRODUCTION

The previously unrecognised Greendale Fault ruptured during the shallow-focus (~11 km deep) M_w 7.1 Darfield earthquake of 4 September, 2010 (NZST). The earthquake epicentre was located ~8 km southeast of Darfield township (Figure 1), and ~37 km west of the centre of Christchurch, New Zealand's second largest city. This event marked the end of a 23-year hiatus since the last ground-surface fault rupture in New Zealand, during the 1987 M_w 6.3 Edgecumbe earthquake, Bay of Plenty, North Island (Beanland *et al.* 1989, 1990). Surface rupture of the Greendale Fault extends west-east for at least 29.5 km across gravel-dominated alluvial plains (Figure 1). Surface displacement is predominantly dextral strike-slip, expressed on left-stepping, en echelon traces across the low relief and exceptionally maintained pastoral landscape of the Canterbury Plains (Figures 1, 2, 3 & 5), which affords an ideal environment for characterising even the most subtle of earthquake-related ground deformation at high resolution. This paper presents an initial summary of the surface rupture deformation features produced during the Darfield earthquake. Seismological (e.g. Cousins & McVerry 2010, Gledhill *et al.* 2010) and geodetic (Beavan *et al.* 2010) aspects of the earthquake are addressed elsewhere in this volume.

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GREENDALE FAULT SURFACE RUPTURE

A Rapid and Coordinated Scientific Response

Immediately after the earthquake (4:35 am), earth scientists from the University of Canterbury (UC) rushed to inspect earthquake damage in Christchurch and provide immediate information to the public via media. Within three hours of the earthquake, a fault rupture reconnaissance and response team had been deployed, led by scientists from the UC Active Tectonics team and the GNS Science Earthquake Geology and Geological Mapping teams. Fanning out towards the epicentral area, the locally-based UC team located the first evidence for ground-surface fault rupture at 9:30 am and began to assess hazards to the affected community and conduct measurements of fault offsets across roads and fences. Upon arrival in the region, GNS scientists undertook a helicopter reconnaissance flight to define the limits of obvious surface deformation and to photograph key features (e.g. Figures 2A, 2C, 3 & 5). By the end of Day 1, a first approximation of the surface rupture length and general damage patterns had been established, and formed the basis for planning the scientific documentation of the event. Priorities were set to rapidly examine features that: a) posed a potential

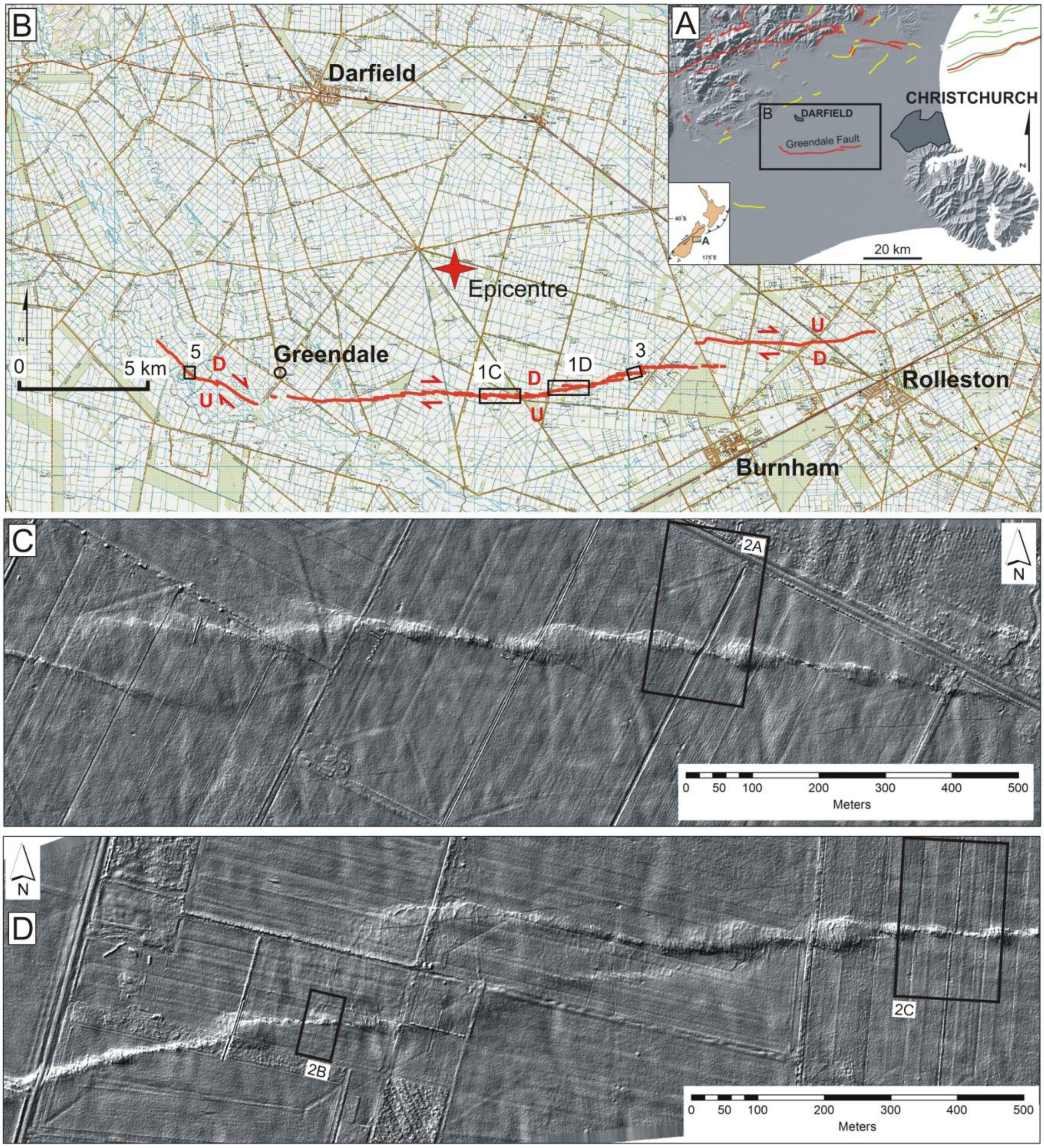

Figure 1: ***A) DEM of the Christchurch area of the Canterbury region showing location of the Greendale Fault and other tectonically active structures. Red lines are active faults, and yellow and green lines are, respectively, on-land and off-shore active folds (combined data from Forsyth et al. (2008) and GNS Active Faults Database). B) Mapped surface trace of the Greendale Fault. Red arrows indicate relative sense of lateral displacement, while vertical displacement is denoted by red U = up and D = down. Also shown are locations of Figures 1C, 1D, 3 & 5, and Darfield earthquake epicentre (red four-pointed star). C & D) LiDAR hillshade DEMs (illuminated from the NW) of two ~1.5 km long sections of the Greendale Fault, showing characteristic left-stepping en echelon rupture pattern, and dextral offset of roads, fences, hedges and crop rows. Also shown are locations of Figures 2A, 2B & 2C.***

risk to people (e.g. fault scarps in close proximity to houses, landslides/surface cracks in elevated areas), and b) were likely to be removed quickly by land remediation and infrastructure repair (e.g. cracks in roads, deformed power lines). The rapid collaborative scientific response ensured that these fault deformation features were accurately documented prior to their removal.

In the weeks following the earthquake, a variety of methods including tape and compass, differential and Real Time Kinematic (RTK) GPS surveys, and terrestrial laser scanning were used to map the Greendale Fault in high resolution. The location of the fault rupture in an agricultural landscape that contains numerous linear features such as roads, fences, hedge-rows, irrigation channels, and power lines provided a wealth of fault displacement markers. In some places, fault offsets of < 100 mm were able to be documented using these anthropogenic markers. Progressive iterations of maps of the surface rupture were made available to the public on-line and presented to local and regional councils as well as landowners. Airborne LiDAR (Figures 1C & 1D) and vertical aerial photographs were acquired over ~20 km of the Greendale Fault six days after the event. Post-mainshock surface 'creep' across the Greendale Fault is being monitored at several locations by repeat Total Station surveys (~2 to 3 times per month), and off-fault deformation is being precisely measured by reoccupation of pre-earthquake cadastral surveys. As a consequence, a rich dataset of fault deformation, displacement, buckling and detailed fracture patterns has been obtained for the full length of the surface rupture. Fault data continue to be analyzed by GNS and UC personnel. When complete, the dataset will represent the most comprehensive and detailed collation of ground-surface fault rupture characteristics of any earthquake in New Zealand, and one of the best documentations of surface rupture world-wide. The surface rupture dataset is currently being combined with seismological and geodetic datasets and, collectively, they are yielding exciting insights into the rupture process and dynamics of the Darfield earthquake (e.g. Beavan *et al.* 2010, Gledhill *et al.* 2010, Holden *et al.* 2010).

Surface Fault Displacement and Expression

The zone of identified surface rupture extends from ~4 km west of the hamlet of Greendale for about 29.5 km to an eastern tip ~2 km north of the town of Rolleston (Figure 1). The fault was named the Greendale Fault by the fault rupture reconnaissance and response team. The gross morphology of the surface rupture is that of an en echelon series of east-west striking, left-stepping surface traces (Figure 1). The largest step-over is ~1 km wide, located ~7 km from the eastern end of surface rupture, with another ~20 step-overs between 300 and 75 m wide, and a multitude of smaller ones. Push-up structures have formed at most of these restraining left-steps, with amplitudes up to ~1 m, but typically < 0.5 m (Figures 1C & 1D).

Many well-defined straight features were offset by the fault (Figure 2), allowing the amounts and styles of displacement to be measured with high precision at more than 100 localities along the entire length of surface rupture. Average displacement over the full length of surface rupture is ~2.5 m (predominantly dextral), and is distributed across a ~30 to 300 m wide deformation zone, largely as horizontal flexure. On average, 50% of the dextral displacement occurs over 40% of the total width of the deformation zone. Offset on discrete shears, where present, typically accounts for only a minor percentage of the total displacement. Across the paddocks

Figure 2: ***Oblique aerial photographs of Greendale Fault surface rupture (see Figures 1C & 1D for locations). Lateral displacement is distributed across a deformation zone of several tens of metres width; red arrows indicate relative sense of lateral displacement. A) 4.5 to 5 m of dextral displacement of a single-lane gravel road. Photo taken by Simon Cox about 11 hours after the earthquake looking north. B) ~3.5 m of dextral displacement of two wire fences and a row of small pine trees. Photo taken by Richard Cosgrove several days after the earthquake looking north. C) 4.5 to 5 m of dextral displacement of a hedge-row (wind break) of pine trees and tractor tyre tracks. Photo taken by David Barrell about 11 hours after the earthquake looking north.***

deformed by fault rupture, there is a threshold of surface rupture displacement of ~1.5 m above which discrete ground cracks and shears occur and form part of the surface rupture deformation zone, and below which they are not present. The distributed nature of Greendale Fault surface rupture displacement no doubt reflects a considerable thickness of poorly consolidated alluvial gravel deposits underlying the plains.

The distribution of surface rupture displacement is approximately symmetrical along the fault, with ~6 km at either end of the fault where overall displacement is less than ~1.5 m, and an ~8 km long central section where net displacement is > 4 m, with maxima of ~5 m (Table 1). Over the reach of the fault where displacement exceeds the average, the deformation zone comprises east-southeast striking Riedel fractures with right-lateral displacements, southeast striking extensional fractures, south-southeast to south striking Riedel fractures with left-lateral displacements, northeast striking thrusts, horizontal dextral flexure, and decimetre-amplitude vertical flexure and bulging (Figure 3).

Vertical throw across the full width of the surface rupture deformation zone is typically < 0.75 m. Generally the south side is up, though the eastern ~6 km of rupture is north-side up. Vertical displacement increases locally to ~1 to 1.5 m at major restraining and releasing bends

The trace of the Greendale Fault extends across a Late Pleistocene braidplain of subdued fluvial bars and channels of similar or greater topographic relief than the deformation caused by the surface rupture. Without distinct linear markers such as fences, we probably would have identified no more than ~70% of the surface rupture length. As fissures heal and bumps smooth out, the ability to discern the fault trace, without reference to man-made features, will diminish further. As a consequence, the length of surface rupture preserved, or discernable, in the geological record will be a significant underestimate of the true surface rupture length. This has implications for future seismic hazard assessment in the region and the search for possible past Greendale-type ruptures elsewhere.

Table 1. Amounts of surface rupture displacement along the Greendale Fault.

Net surface rupture displacement	Cumulative length of surface rupture
< 1.5 m	12 km
1.5 to 2.5 m	3 km
2.5 to 4 m	6.5 km
> 4 m	8 km
Average ~2.5 m	Total ~29.5 km
Maximum ~5 m	

The Greendale Fault has a notably large surface rupture displacement (both maximum and average) for its surface rupture length when compared to international datasets of historic surface rupture earthquakes (e.g. Wesnousky 2008, Wells & Coppersmith 1994), raising the possibility that it is a high stress-drop rupture. Also, based on the currently known surface rupture length of the Greendale Fault, the magnitude of the Darfield earthquake (M_w 7.1) would be underpredicted using the magnitude/rupture-length regressions in the above

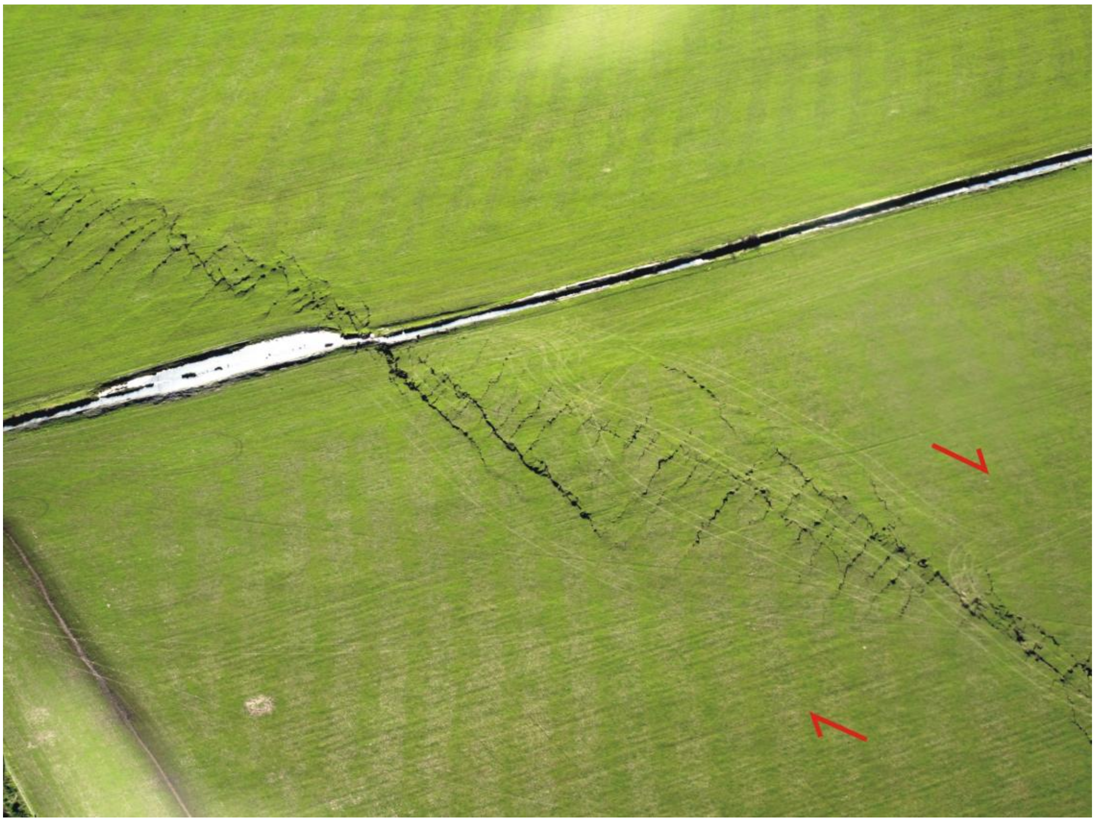

Figure 3: ***Oblique aerial photograph of Greendale Fault surface rupture (see Figure 1B for location). Red arrows indicate relative sense and width of lateral displacement. Here, ~3.5 m of dextral displacement is distributed across a deformation zone up to 40 m wide comprising Riedel shears, conjugate Riedel shears, horizontal dextral flexure, and decimetre-amplitude vertical flexure and bulging. Photo taken by Richard Jongens about 11 hours after the earthquake looking northwest.***

two papers (M_w 6.8 for both Wesnousky 2008 and Wells & Coppersmith 1994), and a recently developed regression for low slip-rate reverse and strike-slip New Zealand earthquakes (equation 1 in Stirling *et al.* 2008; M_w 6.9, assuming sub-surface rupture length is about 15% longer than surface rupture length). However, preliminary seismological (Gledhill *et al.* 2010, Holden *et al.* 2010) and geodetic (Beavan *et al.* 2010) interpretations of the rupture process of the Darfield earthquake attribute a component of the total moment release to a precursor blind thrust rupture, suggesting that the moment associated with the rupture of the Greendale Fault was less than the total for the earthquake as a whole. Preliminary modelling of the Greendale Fault component of the Darfield earthquake results in a M_w of 6.9 based on seismological data (Holden *et al.* 2010), and M_w 7.0 from geodetic data (Beavan *et al.* 2010), similar to the M_w derived from the empirical regressions considering Greendale Fault rupture alone.

The Greendale Fault ruptured primarily across the 'Burnham' surface, abandoned by rivers at the end of the Last Glaciation (Forsyth *et al.* 2008). No evidence of previous faulting had been recognised, either prior to the earthquake or in retrospective examination of pre-earthquake aerial photo-graphs. However, thorough cultivation of the Canterbury Plains following the arrival of Europeans in the mid 1800s has subdued some detail of the original river channel form. Coupled with the small and distributed vertical offset along much of the new fault trace, and the possibility that previous earthquakes may not have produced significant surface rupture, there is reason for caution in drawing preliminary conclusions of the long term earthquake history of the Greendale Fault.

Effects on Man-Made Structures and Property

Over a dozen buildings, typically timber-framed houses and farm sheds with light-weight roofs, lay either wholly, or partially, within the Greendale Fault surface rupture deformation zone. None of these buildings collapsed, even the two with 0.5 to 1 m of discrete shear extending through/under them (Figure 4A), but all were more damaged than comparable structures immediately outside the zone of surface rupture deformation. Some of the properties worst damaged by fault rupture have been condemned. From a life safety standpoint, all these buildings performed satisfactorily, but with regard to post-event functionality, there are notable differences. The houses with concrete slab foundations (typically brick-clad) suffered moderate to severe structural and non-structural damage, while a light industrial building with a more robust concrete slab, and the two piled structures (Figure 4B) were less damaged and will be more straightforward to reinstate.

In 2003, the Ministry for the Environment (MfE), New Zealand, published best practice guidelines for mitigating fault surface rupture hazard (Kerr *et al.* 2004, MfE Active Fault Guidelines. Also see Van Dissen *et al.* 2006). Key rupture hazard parameters in the MfE Active Fault Guidelines are Fault Complexity along with Building Importance and fault recurrence interval. Where rupture is distributed over a wide area, the amount of deformation at a specific locality within the distributed zone is less compared to where the deformation is concentrated on a single well-defined trace. The relative fault rupture hazard is therefore less within a zone of distributed deformation than it would be within a narrow well-defined zone. Surface rupture displacement on the Greendale Fault was typically distributed across a relatively wide zone of deformation. Buildings located within this distributed zone of deformation were subjected to only a portion of the fault's total surface rupture displacement, and no structure within this zone collapsed. This provides a clear example of the appropriateness of the MfE's *Distributed* Fault Complexity parameter, at least for Building Importance Category 2a structures (i.e. residential structures).

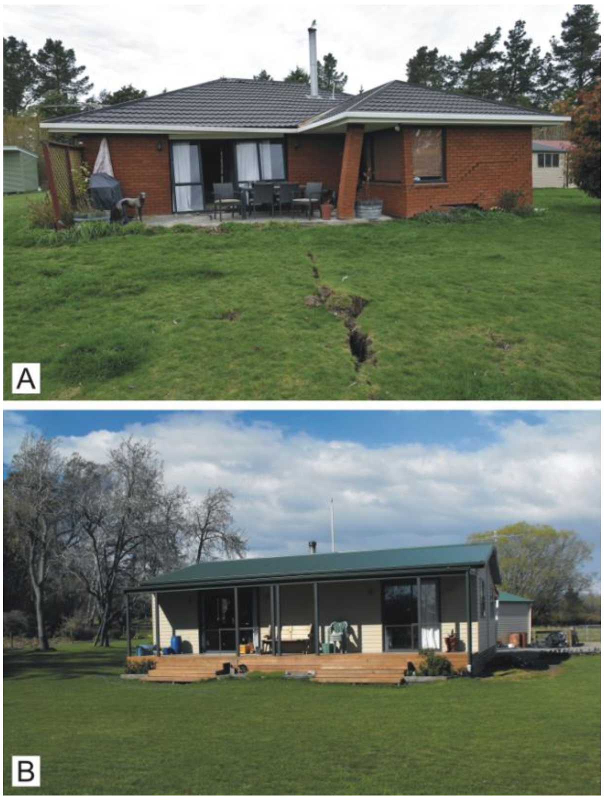

***Figure 4.** Examples of houses affected by Greendale Fault surface rupture. A) Timber-framed, brick-clad house with concrete slab foundation and light-weight roof that is located within a ~150 m wide deformation zone accommodating 4 to 5 m of dextral displacement. House is badly damaged by ~0.5 m of discrete strike-slip rupture that passes through the foundation of the house as well as distributed shear within the broad deformation zone. Photo by Dougal Townsend. B) Light-gauge steel framed, plywood- and weatherboard-clad house with steel pile foundation and steel I-beam bearers that is tilted, and rotated, but only slightly damaged, by ~1 m of distributed vertical and dextral fault rupture spread over several tens of metres width. Photo by Russ Van Dissen.*

Some irrigation channels flooded due to the fault displacements, other ground disturbance and/or changes in groundwater tables. The most spectacular and extensive flooding caused by fault rupture occurred at the Hororata River, near the western end of the fault (Figures 1B & 5), where ~1 to 1.5 m of both dextral and vertical (southwest-side up) rupture extended across the river, partially blocking its channel, and resulting in partial avulsion. Deepening of the channel downstream of the fault rupture, via two backhoes, was required in order to return the full river flow to its original channel position.

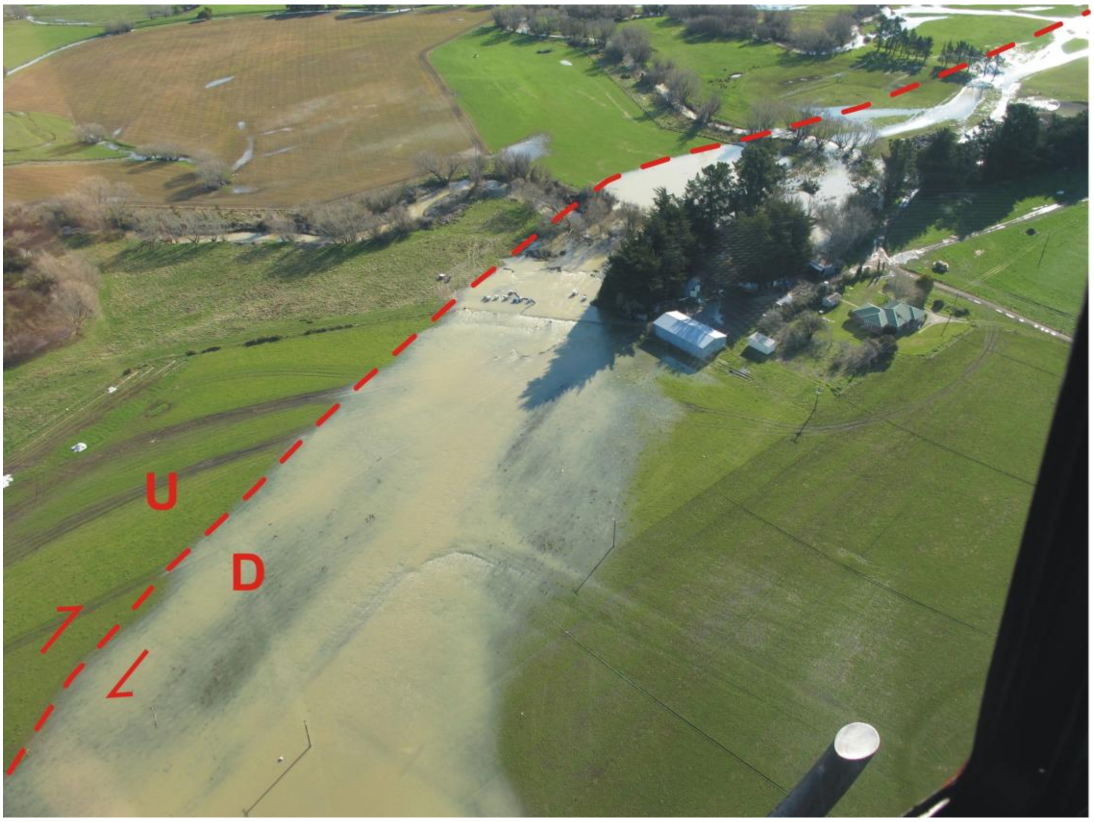

***Figure 5:** Oblique aerial photograph of Greendale Fault surface rupture and partial avulsion of the Hororata River (see Figure 1B for location). Hororata River flows right to left (i.e. southeast), location of Greendale Fault is denoted by dashed red line with relative sense of lateral displacement shown by red arrows, and relative vertical displacement indicated by red U = up and D = down. Here, ~1.5 m of oblique dextral southwest-side up rupture of the Greendale Fault extended across the Hororata River, partially blocking the river's channel, and leading to partial avulsion and significant flooding of dairy farmland. Photo taken by David Barrell about 11 hours after the earthquake looking west.*

Fences, roads, power and telephone lines, irrigation channels and underground pipes were also deformed by Greendale Fault rupture, with damage commensurate with the type of feature, its orientation with respect to the fault, and the amount, sense and width of surface rupture deformation. Of particular note, linear features that spanned all, or part, of the surface rupture deformation zone, as well as being displaced across the fault, were also subjected to lengthening, or shortening, depending on their orientations with respect to the dextral shear direction (e.g. Taylor & Cluff 1977).

Substantial damage occurred within pine forest plantations throughout the area. Many trees within the surface rupture deformation zone were damaged, tilted, and/or felled due to faulting of root systems. In a wider area around the fault, a surprising number of trees blew down during strong NW winds in the days following the earthquake. This possibly reflects the loosening of tree root zones due to strong earthquake shaking.

OTHER POSSIBLE SURFACE RUPTURE FEATURES

Large earthquakes are commonly characterized by a rupture process involving slip on more than one fault (e.g. 2002 M_w 7.9 Denali earthquake, Eberhart-Phillips *et al.* 2003; 2010 M_w 7.0 Haiti earthquake, Hayes *et al.* 2010). In the case of the Darfield earthquake, preliminary seismological (Gledhill *et al.* 2010, Holden *et al.* 2010), geodetic (Beavan *et al.* 2010), and geological field evidence all suggest that this earthquake was associated with smaller-scale rupture on other faults in addition to the main rupture on the Greendale Fault. An area ~3 km southwest of Hororata township is characterized by: a) portions of over-tightened and tension-damaged wire fences and localized road cracking that appears to define a NE-SW trending damage zone, b) a NE-SW trending belt of aftershock epicentres that includes some $M_L > 4$ thrust-sense events with NW-SE dipping focal planes, and c) a NE-SW trending area of 'towards satellite' motion of ~1 m on the ALOS and Envisat interferograms presented in Beavan *et al.* (2010; their figures 3-5). Interpretations of seismic reflection data (Forsyth *et al.* 2008) suggest the presence of an unnamed NW-dipping thrust fault underlying this area. Collectively, the evidence is suggestive of some surface uplift, perhaps in the form of bulging rather than discrete fault offset, relating to slip on a thrust fault at depth. Documenting fault rupture on any other structures around the periphery of the unequivocal area of surface rupture fault deformation would provide additional insights into the dynamics of the rupture process and relationship between total rupture area, seismic moment release and small-scale changes in surface topography. Ongoing collaborative research between students and staff at UC and scientists from GNS is focused on documenting "peripheral" deformation and distinguishing fault-related deformation from deformation resulting from other causes such as ground-shaking, and/or liquefaction.

CONCLUSIONS

The M_w 7.1 Darfield (Canterbury) earthquake of 4 September 2010 (NZST) was the first New Zealand surface-rupture earthquake since the 1987 Edgecumbe earthquake, and the first surface-rupture earthquake in New Zealand since publication of the MfE Active Fault Guidelines.

During the Darfield earthquake, surface rupture of the previously unrecognised Greendale Fault extended west-east for at least 29.5 km across alluvial plains west of Christchurch. Surface rupture displacement is predominantly dextral strike-slip with maxima of ~5 m, and an average of ~2.5 m. Displacement is distributed over a ~30 to 300 m wide zone, and is accommodated, mainly, via horizontal dextral flexure. Vertical deformation is typically decimetre-amplitude vertical flexure and bulging, but at several major fault bends, vertical displacement reaches ~1 to 1.5 m.

Over a dozen buildings (timber-framed houses and farm sheds) were directly impacted by Greendale Fault surface rupture. None collapsed, though all suffered more structural damage than comparable buildings outside the surface rupture deformation zone. This earthquake highlights the value of the *Distributed* Fault Complexity parameter of the MfE Active Fault Guidelines.

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