Photographic Feature

Strike-slip ground-surface rupture (Greendale Fault) associated with the 4 September 2010 Darfield earthquake, Canterbury, New Zealand

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Abstract: This paper provides a photographic tour of the ground-surface rupture features of the Greendale Fault, formed during the 4 September 2010 Darfield earthquake. The fault, previously unknown, produced at least 29.5 km of strike-slip surface deformation of right-lateral (dextral) sense. Deformation, spread over a zone between 30 and 300 m wide, consisted mostly of horizontal flexure with subsidiary discrete shears, the latter only prominent where overall displacement across the zone exceeded about 1.5 m. A remarkable feature of this event was its location in an intensively farmed landscape, where a multitude of straight markers, such as fences, roads and ditches, allowed precise measurements of offsets, and permitted well-defined limits to be placed on the length and widths of the surface rupture deformation.

The M_w 7.1 Darfield earthquake, centred about 40 km west of the city of Christchurch, New Zealand, struck at 4:35 a.m. on 4 September 2010, shattering the pre-dawn darkness with a deafening roar and violent shaking. The rising sun illuminated a newly formed fault trace, aligned roughly west–east across farmland of the Canterbury Plains (Fig. 1). The earthquake created very strong, damaging, ground motions in the Canterbury region and was felt through much of New Zealand (Cousins & McVerry 2010; Gledhill *et al.* 2010, 2011). Fortunately, there were no fatal injuries and only two people were reported to have been seriously injured. However, damage to building contents, building structures, roads and utilities, particularly in low-lying coastal areas where liquefaction was severe (Cubrinovski *et al.* 2010), was assessed as being likely to run to several billion New Zealand dollars. Circumstances changed tragically on 22 February 2011, when a shallow-focus aftershock of M_w 6.3 struck 10 km SE of the Christchurch city centre (Reyners 2011). The Christchurch earthquake caused much more severe damage to the city than did the Darfield earthquake, with the loss of about 182 lives, many injuries, and serious social and economic disruption. However, the focus of this paper is confined to the Greendale Fault surface rupture (Fig. 1) formed in the 4 September 2010 Darfield earthquake.

Discovery

Within 3 h of the earthquake, a fault rupture reconnaissance and response team had been deployed, led by scientists from University of Canterbury Department of Geological Sciences (UC) and from GNS Science (GNS), New Zealand's government-owned earth science research institution. Fanning out towards the epicentre, the locally based UC team had, about 5 h after the earthquake, located evidence for ground-surface fault rupture and began examining and measuring the rupture zone, and assessing associated hazards to the affected community. Upon arrival in the region, about 8 h after the earthquake, GNS scientists took a helicopter reconnaissance flight and established that at least 16 km of surface rupture were visible from about 200 m altitude. Within 36 h of the earthquake, ground-based reconnaissance had established a surface rupture length of about 22 km. Over the following 2 weeks, detailed mapping extended this by a further 7.5 km, to a total of *c*. 29.5 km (Fig. 1) (Quigley *et al.* 2010*a*,*b*; Van Dissen *et al.* 2011).

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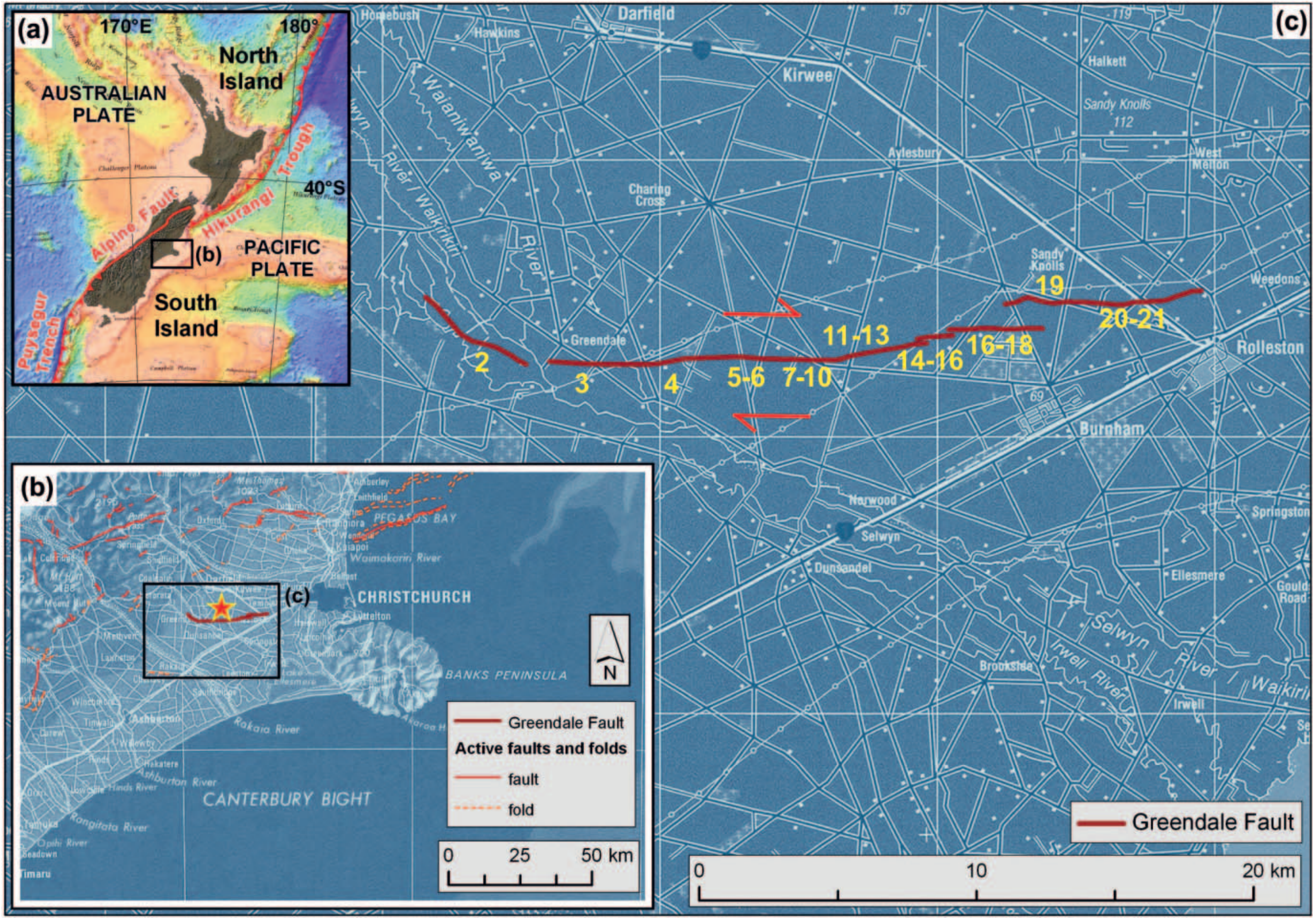

Fig. 1. Location and neotectonic setting. (**a**) Bathymetry of the New Zealand region (orange, shallow; blue, deep; image courtesy of GNS Science), annotated with the plate tectonic setting. (**b**) The Greendale Fault in relation to mapped active faults (red) and folds (orange), from Cox & Barrell (2007) and Forsyth *et al.* (2008), and the Darfield earthquake epicentre (star). (**c**) Generalized map of the Greendale Fault ground surface deformation; the numbers denote the locations of photographs in Figures 2–21. The map images are derived from NZMS 266 (**b**) and Topo250 (**c**) topographic maps of New Zealand, copyright Land Information New Zealand.

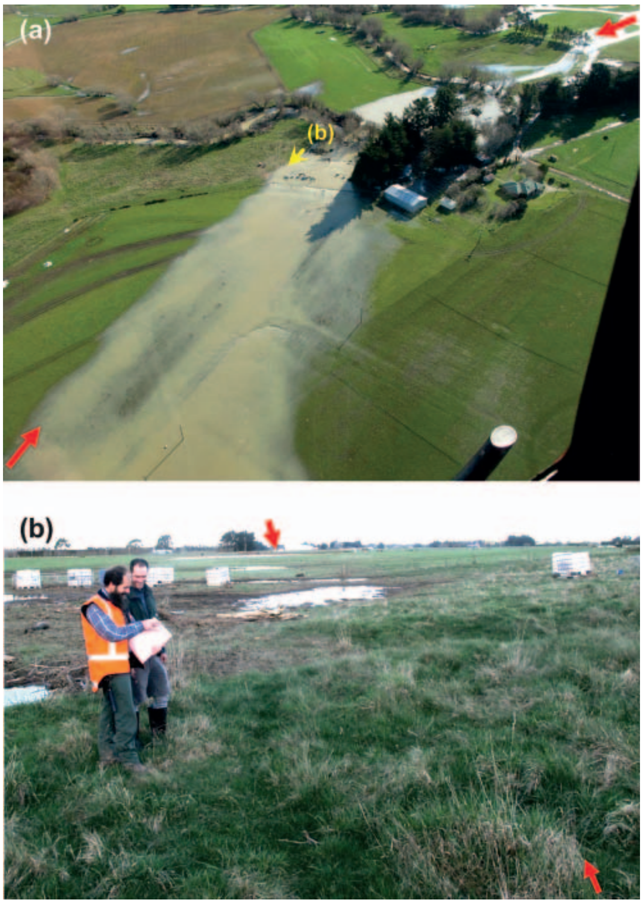

Fig. 2. (**a**) The sinuous course of the Hororata River, flowing from upper right to upper left, is crossed by the fault in this westward view, taken 4 September. A significant portion of the river's flow is diverted towards the lower left, along the downthrown side of the fault. (**b**) In this view SE from location shown in (a), taken 15 September, the broad rise up to the right is the fault, which here has bent rather than broken the ground. Excavation of the river channel has stemmed the overflow across farmland.

Fig. 4. (**a**) Progressing eastward, where the horizontal flexure exceeds 2 m, ground cracking became increasingly evident, as seen across the farm lane in this view to the south. (**b**) Detail of the form and depths of tension cracks seen in (**a**), looking NE, on 5 September.

Fig. 3. This view south along an originally straight fence in a formerly flat field illustrates the oblique right-lateral (*c.* 1 m) and up-to-south (*c.* 1 m) ground flexure that characterizes the western end of the Greendale Fault.

Fig. 5. This northward aerial view at Stranges Road highlights Reidel shears, at a low angle to the strike of the fault, each with as much as 1 m lateral offset, as seen across the vehicle ruts. However, most of the *c.* 4.5 m right-lateral displacement is by horizontal flexure, as shown by the hedgerow and irrigation ditch. Flow in the ditch was impeded by slight upthrow to the south, but the ditch had been deepened prior to this photograph on 9 September.

Fig. 6. At Courtenay Road, this northward view shows team members carrying out a precise real-time kinematic global positioning system (GPS) survey of a right-lateral offset (*c.* 4.3 m) of the formerly straight fenceline. The deformation occurred over a *c.* 35 m wide zone, and the ground is broken by discrete shears right of centre.

Fig. 8. An aerial view looking NE showing en echelon Reidel shears that narrowly miss a house, but pass through its garage.

Fig. 7. This view looking south shows the surface fault rupture where most of the lateral displacement (*c.* 4.6 m) is concentrated within a narrow zone, with 'mole tracks' (displaced turf) evident along shears that displace the fenceline.

Fig. 9. In this telephoto view north along Telegraph Road, the busiest road to have been crossed by the fault rupture, the Greendale Fault has displaced the road right-laterally by approximately a lane width. Being a major rural thoroughfare, initial repairs were undertaken on the day of the earthquake.

Setting

Named after the hamlet of Greendale near the western end of the fault (Fig. 1), the predominantly strike-slip ground surface rupturing fault, with a right-lateral (dextral) sense of displacement, traversed gravelly alluvial plains. The surface of this sector of the Canterbury Plains dates from the end of the Last Glaciation, with post-glacial incised degradation terraces adjacent to active river channels (Forsyth *et al.* 2008). Relict, generally subtle, river channel and bar patterns on the plains are thoroughly overwhelmed by the human geomorphological footprint, comprising a matrix of straight linear features such as fences, roads, power lines, crop rows and irrigation ditches. Along the full length of the surface trace, rarely is there a stretch of more than 300 m without a human-made (formerly) straight line.

The boundary between the Australian and Pacific plates bisects New Zealand (Fig. 1a). The Pacific plate is moving WSW relative to the Australian plate, at

Fig. 10. (**a**) A shear with about 0.5–1 m of right-lateral displacement passed through this modern, timber-framed, brick-clad farmhouse. Despite undergoing severe structural damage, the house remained standing and its occupants were unharmed. (**b**) A view looking west at the opposite side of the house shown in (**a**).

48 mm a^{-1} in northeastern New Zealand, decreasing to 39 mm a^{-1} in the SW (Wallace *et al.* 2007). Between the Puysegur and Hikurangi subduction thrusts, the oblique dextral strike-slip/reverse Alpine Fault is the locus of

Fig. 11. A view south down Highfield Road, the second of only two tarsealed roads to have been crossed at a high angle by the fault in its high-displacement central section. Being a minor road, several days passed before repairs were made to the spectacular array of shears and cracks across the tarseal. In the mean time, the site became a local tourist attraction because it was one of the few fault rupture locations that was both undisturbed and publicly accessible. Here, localized bulging resulted in an upthrow of more than 1 m, creating a visual phenomenon in concert with the *c*. 4.5 m right-lateral offset of the carriageway, roadside fences and hedgerows.

plate boundary movement in the South Island. A small portion of the plate motion is accommodated by a broad zone of active deformation SE of the Alpine Fault, with many active faults and folds (Fig. 1b). The Greendale Fault lies near the SE margin of this deformation zone. No prior indication had been found of a fault at this location. Regional geological mapping of this area in the mid-2000s had not found any surface evidence of a fault scarp on this part of the Canterbury Plains (Forsyth *et al.* 2008), although the field work was generally limited to drive-by reconnaissance. Also adding to the surprise of the emergence of the Greendale Fault was that this part of Canterbury has had only a low level of historical seismicity (Stirling *et al.* 2008).

Fig. 12. Members of the fault rupture reconnaissance team measure offsets (*c*. 3.6 m) of a fenceline a few hundred metres east of Highfield Road, view looking south.

Fig. 13. This view east along the fault displays a spectacular pattern of conjugate Reidel shears at a high angle to the strike of the fault, which curves off towards the upper left. The fence in the mid-ground is the same one as shown in Figure 12.

Fig. 14. A northward aerial view of a narrow fault zone (left) diffusing into a broad flexure across the ploughed fields, then narrowing into a shear near the crops to the right. Total right-lateral displacement of these features is *c*. 4.5 m.

Fig. 15. (**a**) Arrays of shears and localized bulges are seen in this aerial view looking north. The irrigation ditch is displaced laterally by *c*. 3.5 m. (**b**) Following initial science reports to the media, stating that there was no prior knowledge of a fault in this area, a landowner ploughed these words into this field. The words reference a nationwide billboard advertising campaign for a brand of beer, in which a bold statement is made, alongside which are the words 'yeah, right', indicating that a sensible person would not believe the statement. The view is SW, and the features shown in (**a**) are upper left from centre.

Description

The westernmost *c*. 6 km of the surface trace has a NW–SE strike and displays oblique dextral and south-side-up vertical displacement (net) of as much as 1.5 m (Figs 2 and 3). Movement was accommodated by ground flexure, with few, if any, surface shears. Net upthrow to the south caused partial avulsion of the Hororata River (Fig. 2a), although this was rectified within a few days by deepening of the natural channel using excavators.

In the central *c*. 15 km of the surface trace, displacement exceeds *c*. 2.5 m, expressed on left-stepping, en echelon traces (Figs 5–18). Deformation is distributed across a 30–300 m wide zone, mainly via horizontal flexure but with discrete Riedel shears and conjugate

Fig. 16. A close-up view of shears within a field. Their expressions are particularly clear on account of the very short grass. The total right-lateral displacement at this site is *c*. 3.5–4 m.

Fig. 17. Where shears crossed belts of trees, commonly the trees were loosened from the soil, or uprooted. This was one rare instance where a shear split a tree in two, in this case a juvenile *Pinus radiata* with trunk diameter of *c*. 0.15 m.

Riedel shears. Along the central 8 km of surface rupture, lateral displacement exceeds 4 m and the fault trace was obvious to even the untrained eye, with roads and fences bent and sheared sideways by as much as 5 m (see Figs 5–14).

Fig. 19. On the eastern strand of the fault, deformation comprised horizontal flexure, with very little cracking of the ground. For the most part, cracks were evident only where the fault crossed a relatively brittle feature such as a tarsealed road. In this view southward, the fence reveals a right-lateral flexure of about 1.3 m.

Towards the east, the deformation stepped about 1 km to the north, forming a separate trace, which represents the easternmost *c*. 6 km of the fault (see Fig. 1). On this eastern trace, dextral displacement is no more than about 1.5 m, virtually all accommodated by horizontal flexure (Figs. 19 to 21).

Vertical displacement is most prominent at the western end of the fault (see above). Elsewhere, the overall vertical component is rarely more than 0.5 m, but with localized push-ups, of as much as 1.5 m, formed at most of the numerous en echelon left-steps. The south side is up everywhere except at the eastern end of the fault, which is north side up. The scale of vertical deformation is comparable with the natural relief of fluvial landforms on the Canterbury Plains. For most of the length of the fault, without the broken ground (e.g. ‘mole tracks’ (displaced turf)) or linear markers such as fences, the fault would not have been readily discernible, and will

Fig. 18. (**a**) An aerial view north showing shears crossing an irrigation ditch (right-lateral offset of *c*. 2.6 m) and passing through a farm shed. The left-hand side of this building is shown in (**b**). (**b**) Members of the fault rupture reconnaissance team measure the effects of a shear, its mole track evident in the foreground, on the farm shed.

Fig. 20. In this view northeastward, the painted centreline of Kerrs Road displays a right-lateral flexure of about 1.5 m. An array of minor cracks formed across the road in the flexure zone. Without straight linear features such as roads and fences, this deformation would be indiscernible.

Fig. 21. Near the eastern limit of recognized deformation, the fault crossed the South Island Midland Railway. This view southward illustrates a broad right-lateral flexure of *c.* 1 m of the line of the rails. As the rail embankment tends to smooth over the minor natural fluvial irregularities of the plains, the rails were an excellent datum for estimating the vertical component of offset. Precise GPS surveying indicated *c.* 0.4 m of upthrow to the north at this location. During the earthquake, one section of the rails was kinked sideways to the left (east). This photograph was taken on 5 September, immediately after replacement of the kinked rail section. The new rails are rusty as they have yet to be polished by train movement.

become less so over time, as fissures fill and bumps smooth over.

In many of the photographs in this paper, red arrows are used to denote the approximate position and strike of the fault trace.

Summary

Perhaps the most remarkable feature of this strike-slip ground surface rupture is that it occurred within a landscape containing a myriad of straight lines. These provided perfect ‘piercing points’ for measuring the amounts and styles of fault deformation. Moreover, these straight lines made it easy to see deformation features as subtle as 1 m horizontal flexures of the ground that were several tens of metres wide, which were not even accompanied by discernible cracking of the ground surface. As a result, it was possible to document the character and extent of the Greendale Fault, as revealed during the 4 September 2010 Darfield earthquake, to a spectacular level of precision.

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References

Cousins, J. & McVerry, G. 2010. Overview of strong-motion data from the Darfield earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, **43**, 222–227.

Cox, S.C. & Barrell, D.J.A. (compilers) 2007. *Geology of the Aoraki area*. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 15. GNS Science, Lower Hutt.

Cubrinovski, M., Green, R.A. *et al.* 2010. Geotechnical reconnaissance of the 2010 Darfield (Canterbury) earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, **43**, 243–320.

Forsyth, P.J., Barrell, D.J.A. & Jongens, R. (compilers) 2008. *Geology of the Christchurch area*. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 16. GNS Science, Lower Hutt.

Gledhill, K., Ristau, J., Reyners, M., Fry, B. & Holden, C. 2010. The Darfield (Canterbury) M_w 7.1 earthquake of September 2010: preliminary seismological report. *Bulletin of the New Zealand Society for Earthquake Engineering*, **43**, 215–221.

Gledhill, K., Ristau, J., Reyners, M., Fry, B. & Holden, C. 2011. The Darfield (Canterbury, New Zealand) M_w 7.1 earthquake of September 2010: a preliminary seismological report. *Seismological Research Letters*, **82**, 378–386.

Quigley, M., Villamor, P. *et al.* 2010*a*. Previously unknown fault shakes New Zealand's South Island. *EOS Transactions, American Geophysical Union*, **91**, 469–470.

Quigley, M., Van Dissen, R. *et al.* 2010*b*. Surface rupture of the Greendale Fault during the M_w 7.1 Darfield (Canterbury) Earthquake, New Zealand: initial findings. *Bulletin of the New Zealand Society for Earthquake Engineering*, **43**, 236–242.

Reyners, M. 2011. Lessons from the destructive M_w 6.3 Christchurch, New Zealand, Earthquake. *Seismological Research Letters*, **82**, 371–372.

Stirling, M., Gerstenberger, M., Litchfield, N., McVerry, G., Smith, W., Pettinga, J. & Barnes, P. 2008. Seismic hazard of the Canterbury region, New Zealand: new earthquake source model and methodology. *Bulletin of the New Zealand Society for Earthquake Engineering*, **41**, 51–67.

Van Dissen, R., Barrell, D. et al. 2011. 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. *In:* Ma, Q. & Deam, B. (eds) *Proceedings of the 9th Pacific Conference on Earthquake Engineering, Auckland, New Zealand, 14–16 April, 2011*, Paper 186.

Wallace, L.M., Beavan, R.J., McCaffrey, R., Berryman, K.R. & Denys, P. 2007. Balancing the plate motion budget in the South Island, New Zealand using GPS, geological and seismological data. *Geophysical Journal International*, **168**, 332–352.

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