Surface rupture during the 2010 $M_w$ 7.1 Darfield (Canterbury) earthquake: Implications for fault rupture dynamics and seismic-hazard analysis

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ABSTRACT

The September 2010 $M_w$ 7.1 Darfield (Canterbury) earthquake in New Zealand is one of the best-recorded earthquakes of this magnitude. The earthquake occurred on a previously unidentified fault system and generated 29.5 ± 0.5-km-long surface rupture across a low-relief agricultural landscape. High-accuracy measurements of coseismic displacements were obtained at over 100 localities along the Greendale fault. Maximum net displacement ($D_{max}$) (5.3 ± 0.5 m) and average net displacement ($D_{avg}$) (2.5 ± 0.1 m) are anomalously large for an earthquake of this $M_w$. This data set provides fundamental information on fault rupture processes relevant to seismic-hazard modeling in this region and analogous settings globally.

INTRODUCTION

The documentation of earthquake-induced surface ruptures (e.g., Clark, 1972) is a fundamental component of fault scaling relationships used for seismic-hazard analysis, engineering design criteria, and studies of fault rupture dynamics (e.g., Wells and Coppersmith, 1994; Wesnousky, 2008). Fault rupture data also enable estimation of static stress changes during earthquakes that provide insight into fault strength (e.g., Griffith et al., 2009) and the modeling of past and future earthquakes (e.g., Price and Bürgmann, 2002). Considerable variability exists in the surface rupture length (SRL) of moderately sized (i.e., $M_w$ 7.0 ± 0.1) historical continental earthquakes, from nil (e.g., the 2010 $M_w$ 7.0 Haiti earthquake; Prentice et al., 2010) to many tens of kilometers (e.g., 60 km SRL for the 1940 $M_w$ 7.0 Imperial Valley, California, quake; Trifunac and Brune, 1970), highlighting the importance of combining geologic with seismologic and geodetic data sets in rupture analysis. Short or absent surface ruptures for continental earthquakes may reflect a concentration of coseismic slip at depth (Wesnousky, 2008) and/or coseismic ruptures on several faults without surface breaks (e.g., Hayes et al., 2010).

The 2010 $M_w$ 7.1 Darfield (Canterbury) earthquake, henceforth referred to as the “Darfield” earthquake, occurred at 04:35 on 4 September 2010 New Zealand local time (16:35, 3 September UTC), with an epicenter located ~44 km west of the Christchurch central business district and a hypocentral depth of ~10.7 km (Fig. 1B) (Gledhill et al., 2011). (The Darfield earthquake was followed by a pronounced aftershock sequence, termed the “Canterbury earthquake sequence,” including a $M_w$ 6.2 aftershock located 10 km southeast of the Christchurch central business district at 12:51 on 22 February local time that caused 182 fatalities and an estimated U.S. $10 billion worth of damage [see the GSA Data Repository¹, and Gledhill et al., 2011].)

The earthquake was recorded by dense networks of broadband and strong-motion seismometers (Gledhill et al., 2011), and ground displacements were obtained from global positioning system (GPS) surveying and interferometric synthetic aperture radar (InSAR) (Beavan et al., 2010). Rapidly deployed field teams identified and began to map the surface fault rupture trace only hours after the earthquake (Quigley et al., 2010). The rupture occurred across a relatively flat, post–last glacial alluvial plain (Forstyth et al., 2008) with an extensive agricultural framework. This provided >100 displaced markers (Fig. 2) that could be measured to determine SRL and coseismic displacements.

In this paper, we use real-time kinematic (RTK) and differential (D) GPS surveying, tape measurements, and airborne light detecting and ranging (LiDAR) to document the Greendale fault (GF) surface rupture during the 2010 Darfield earthquake. The rapid collection of field surface rupture data provides an opportunity to reduce the uncertainties in the displacement measurements and geometrical characteristics of earthquake surface rupture. We compare these data with data from other historical surface ruptures associated with earthquakes of similar $M_w$, and discuss the broader implications for fault behavior, $M_w$-displacement-SRL scaling relationships, and seismic-hazard analysis.

GEOLOGIC SETTING

New Zealand occupies the boundary zone between the Pacific and Australian plates, which converge obliquely at rates of 39–50 mm yr⁻¹ (DeMets et al., 2010) (Fig. 1A). In the central South Island, continent-continent collision is characterized by dextral transpression across a series of predominantly NNE- to east-striking active faults throughout the Southern Alps, the Canterbury Plains, and offshore (Pettinga et al., 2001) (Figs. 1A and 1B). Geodetic data indicate ~2 mm yr⁻¹ of contraction oriented at 277° ± 8° across the 125-km-wide Canterbury Plains block with a western boundary defined by the Porter’s Pass–Amberley fault zone (PPAFZ; Fig. 1B) (Wallace et al., 2007). The stress field in the area of the Darfield earthquake is best characterized by a subhorizontal maximum compressive stress ($σ_s$) trending ~115° ± 5° (Fig. 2) (Sibson et al., 2011). Structures in the Canterbury Plains block (Fig. 1B), such as the fault underlying the Hororata anticline (Jongens et al., 1999) and the Springfield fault (Forstyth et al., 2008), deform the post–last glacial alluvial outwash surface, implying Late Pleistocene or Holocene deformation. No evidence for prior surface-rupturing earthquakes was observed in the vicinity of the GF.
SURFACE RUPTURE CHARACTERISTICS

The GF surface rupture was mapped in detail and >100 horizontal (HD), vertical (VD), and net displacements (D) were obtained by measuring offsets of formerly linear features. These include roads, fences, hedgerows, crop and tree lines, irrigation channels, tire tracks, and power lines. Methodological details are provided in the Data Repository.

The mapped surface rupture is 29.5 ± 0.5 km long. Along the eastern ~8 km of the rupture, deformation is expressed as subtle horizontal flexure with no discrete ruptures, fissures, or vertical scarps, and thus was recognized by mapping the deformation of previously straight, well-defined features such as roads and fences. The east and west rupture tips were located by mapping where such features were no longer deformed (see the Data Repository). The uncertainty in fault tip location is ±100 m at the east tip and ±450 m at the west tip. We estimate that no more than ~70% of the total SRL (forthwith "SRLmin"; ~20.6 km) would have been mapped without reference to these man-made features.

The gross fault rupture morphology is that of two definable east-west–striking segments (eastern and central segments) and a NW-striking segment (western segment) collectively referred to as the GF (Figs. 1C and 3). The east and central fault segments are defined as a series of east-west–striking, left-stepping en echelon surface traces (Figs. 1C and 1D). The widest step-over (~950 ± 50 m) measured perpendicular to the average strike of adjacent rupture traces occurs between the east and central segments. The next widest step-over (~500 m) separates the west and central segments. There are another ~20 step-overs between 75 and 250 m wide. The surface rupture zone contains a multitude of features commonly observed within earthquake ruptures dominated by simple shear (e.g., Terres and Sylvester, 1981). These include approximately east-west–striking dextral faults, WNW-oriented synthetic Riedel (R) dextral shear fractures, approximately NNW-oriented antithetic (R′) sinistral shear fractures, approximately NW-SE–oriented tension fractures, approximately NE-SW–oriented folds and thrust/reverse faults, and decimeter-amplitude vertical flexure and bulging (Figs. 1D and 2). Pop-up structures formed at most of the restraining left-steps with amplitudes up to ~1 m (Fig. 1D).

The distribution of HD and D is approximately symmetric along the fault (Figs. 3A and 3C), with ~6 km at either end of the fault where D is ≤1.5 m, and an ~8-km-long central section where D is ≥4 m. HD and D are distributed across a 30–300-m-wide deformation zone, largely as horizontal flexural folding. On average, 50% of D occurs over 40% of the total width of the deformation zone. Discrete faults were
The average strike-slip to dip-slip ratio is ~5:1. 2.5 ± 0.1 m (Fig. 3C; see the Data Repository).

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Generally not observed where D is ≤1.5 m and typically account for only a minor component of D. In the east part of the central fault segment is an ~5-km-long sector where D is ≥5 m. This sector includes D_{min} of 5.3 ± 0.5 m and HD_{min} of 5.2 ± 0.2 m (all displacement errors reported at 2σ; i.e., 95% confidence) (Figs. 3A and 3C). The maximum VD (1.45 ± 0.2 m) occurs ~2 km from the west end of the fault in the western rupture segment (Fig. 3B). VD across the full length of the surface rupture deformation zone is typically <0.75 m (Fig. 3B). VD is generally south-side-up, though the east ~6 km of rupture is north-side-up. VD increases locally to ~1–1.5 m at major restraining and releasing bends. Best-fit curves through the D data yield a best-fit D_{avg} of 2.5 ± 0.1 m (Fig. 3C; see the Data Repository). The average strike-slip to dip-slip ratio is ~5:1.

**DERIVATION OF M_{G}^{C} AND Δσ^{C} USING GEOLGIC DATA**

To investigate whether we would have accurately estimated the M_{G} potential of the GF from surface rupture characteristics alone, as would be employed in paleoseismic analysis, we used the SRL, D_{max} and D_{avg} versus M_{G} global strike-slip earthquake regressions of Wells and Coppersmith (“WC”; 1994) and Wesnousky (“Wky”; 2008) (see the Data Repository for equations) to derive “geologic” estimates of moment magnitude (M_{G}). Using WC, we find M_{G} = 6.8 ± 0.2 for SRL, M_{G} = 6.6 ± 0.2 for SRL_{min}, M_{G} = 7.4 ± 0.1 for D_{max}, and M_{G} = 7.4 ± 0.1 for D_{avg}. Using Wky, we find M_{G} = 6.8 for SRL and M_{G} = 6.7 for SRL_{min}. Using Hanks and Kanamori (“HK”; 1979) (see the Data Repository) and subsurface fault length L = (4/3)SRL = 39.3 km (within error of geodetically derived L from Beavan et al., 2010), crustal rigidity μ = 3 × 10^{11} dyne/cm², and rupture width W = 12 ± 2 km (Gledhill et al., 2011), we find M_{G} = 7.0 ± 0.1 for SRL and 6.9 ± 0.05 for SRL_{min}. Using Berryman et al. (“B”; 2002) (see the Data Repository) we find M_{G} = 7.0 ± 0.1 for L = (4/3)SRL and 6.9 ± 0.1 for L = (4/3)SRL_{min}. Uncertainties in the conversion of SRL to L broaden the error range in M_{G} estimates.

Beavan et al. (2010) calculated the GF-only M_{G} = 7.0 using a GPS and InSAR-derived fault source model. WC and Wky SRL-based regressions thus underestimate the Darfield earthquake M_{G} and are at the low end, albeit within error, of the GF-only M_{G} WC and Wky SRL_{min} regressions significantly underestimate M_{G}. WC D_{max} and D_{avg} regressions significantly overestimate M_{G}. HK and B equations provide SRL-based estimates within error of M_{G} and SRL_{min}-based estimates below M_{G} and within error of the GF-only M_{G}.

Using the surface rupture data and elliptical fault model equation of Madariga (1977; see the Data Repository), we calculate a “geologic” estimate of coseismic static stress drop on the GF rupture (Δσ^{C}) of 13.9 ± 3.7 MPa.

**DISCUSSION**

Our high-resolution documentation of the GF surface rupture provides an exceptional opportunity to investigate earthquake behavior in a relatively low-strain-rate region of an active plate boundary zone. Several interesting aspects of the GF rupture are evident when comparisons of other historical earthquakes (Fig. 4). GF D_{max}/SRL, D_{avg}/SRL, D_{max}/M_{G}^{C}, and D_{avg}/M_{G}^{C} ratios are the highest of any fault rupture in this data set (Fig. 4). This implies that (1) coseismic displacement was exceptionally high for the fault length, (2) maximum fault slip distribution was concentrated at shallow depths, and/or (3) the precision with which this rupture is measured is higher than is typically achievable for most earthquakes. Each of these possibilities has merit. In support of 1 and/or 2, GF D_{avg} and D_{max} are 2.0–2.3 times (using GF SRL) and 1.8–2.0 times (using GF L) the predicted values obtained from SRL versus D_{avg} or D_{max} regressions for global strike-slip earthquakes (e.g., “power-law” from Wesnousky, 2008). Preliminary strong-motion seismic-source models support hypothesis 2 in that modeled maximum GF slip is concentrated at shallow (≤3 km) depths (Holden et al., 2011). With respect to 3, the ability to document rupture endpoints and displacements using agricultural features gives high confidence in the SRL and D data we present. An absence of these features would have reduced our mapped SRL by ~30% and D by an unquantified amount due to the typical distribution of D across ~50–100-m-wide deformation zones that involve only a minor component of offset on discrete faults (Fig. 1D; see the Data Repository). We suspect that SRL and D documentation prior to the development of modern surveying techniques (e.g., RTK GPS, InSAR, LiDAR) and in areas of remote and/or rugged topography, areas similarly underlain by poorly consolidated alluvial deposits that tend to distribute deformation, and/or areas where linear markers are not abundant, may not have achieved the same resolution that was possible in this instance.
Commonly used empirical relationships yield GF estimates of $M_{w} \leq M_{s}$ using SRL and $M_{w} \geq M_{s}$ using $D_{avg}$ and $D_{max}$. This highlights the challenges of using SRL and $D$ data obtained in paleoseismic studies to derive $M_{w}$ potentials for active faults, particularly in areas where natural and/or anthropogenic surface processes have reduced or obscured the geomorphic expression of past surface-rupturing earthquakes. The broadly distributed nature of GF deformation at several locations, together with fault scarps heights less than or equal to heights of the fluvial bars, channels, and dunes comprising the faulted Late Pleistocene surface, suggests that large stretches of the GF rupture will be challenging to recognize in as little as $10^{3}$ yr.

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