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Crustal stress and fault strength in the Canterbury Plains, New Zealand

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ABSTRACT

The $M_w = 7.1$ Darfield (Canterbury) and $M_w = 6.2$ Christchurch earthquakes and related aftershocks in Canterbury, New Zealand have revealed a major hazard in the Canterbury region in the form of the Greendale Fault and a number of associated faults. The strength of these apparently low slip-rate faults may affect the recurrence intervals of subsequent earthquakes. We use P- and S-wave picks from a dataset of aftershocks of the Darfield earthquake to estimate earthquake locations and focal mechanisms. We use S waveforms to determine shear-wave splitting (SWS) parameters and we estimate the azimuth of the axis of maximum horizontal compression (S_{Hmax}) from inversions of focal mechanisms. Two 2D methods of clustering the focal mechanisms for stress inversion are used, one to estimate the regional stress field and another to investigate variations in S_{Hmax} with distance from the Greendale Fault. A 3D method is also used to investigate variations in S_{Hmax} with depth. The tectonic stress field is remarkably uniform and has an average maximum horizontal compressive stress orientation of $S_{Hmax} = 116 \pm 18°$, forming an angle with the average strike of the Greendale Fault of c. 25°. However, several S_{Hmax} estimates along the Greendale Fault from the regional 2D clustering method are sub-parallel to the fault strike ($93.6 \pm 13.1°$, $100.8 \pm 11.5°$ and $100.8 \pm 12.6°$), indicating that the fault may be frictionally weak, in an Andersonian sense. This variation occurs via an anti-clockwise rotation of S_{Hmax} southwards across the Greendale Fault. SWS fast directions (ϕ) generally match nearby S_{Hmax}, suggesting stress-aligned micro-cracks, but ϕ estimates at stations Cch3 and MQZ, which are near known and inferred faults, are sub-parallel to these faults and differ greatly from nearby stress orientations, indicating structure-dependent anisotropy. A lack of seismicity in the area prior to the Darfield earthquake precludes detailed analysis of time variations. However, there are two end member scenarios: if the pre-seismic stress orientation near the Greendale Fault was in the same direction as we have measured after the earthquake, then it was mis-oriented for rupture. Alternatively, if the stress rotated from the average regional orientation during the earthquake, then we can use the rotation to determine that an average of c. 40% of the pre-seismic differential stress on the Greendale Fault was released during the Darfield earthquake.

1. Introduction

In apparent contradiction of laboratory measurements of rock friction (e.g., Byerlee, 1978) and inferences from stress magnitudes measured at boreholes (e.g., Townend and Zoback, 2000), faults along a number of plate boundaries have been shown to be frictionally weak (Jones, 1988; Townend and Zoback, 2004; Balfour et al., 2005; Hasegawa et al., 2011), and the stress fields in some of these areas have been shown to rotate after large earthquakes (Hardebeck and Hauksson, 2001; Hasegawa et al., 2011). The $M_w = 7.1$ Darfield (Canterbury) earthquake of 4 September 2010 (Gledhill et al., 2010; Quigley et al., 2010; Bannister and Gledhill, 2012) has been interpreted as having occurred on a strong fault (Sibson et al., 2011) on the basis of the angle made by the strike of the Greendale Fault with nearby estimates of maximum horizontal stress direction (S_{Hmax}) and the earthquake's high apparent stress (Fry and Gerstenberger, 2011) and stress drop (Quigley et al., 2012) inferred from the fault geometry and seismological data, respectively. Stress orientation estimates can be determined by focal mechanism inversions (Gephart and Forsyth, 1984; Michael, 1987; Arnold and Townend, 2007) and may also be inferred from seismic anisotropy (Crampin, 1994; Miller and Savage, 2001; Boness and Zoback, 2006). Here we use data from the Darfield aftershock sequence to produce a detailed map of stress orientations in the vicinity of the Greendale Fault from focal mechanism inversions and anisotropy from shear-wave splitting estimates and thereby examine whether the Greendale Fault is optimally oriented for failure.

1.1. *The Darfield (Canterbury) earthquake*

The $M_w = 7.1$ earthquake on 4 September 2010 (New Zealand Standard Time, NZST) at Darfield, New Zealand caused surface

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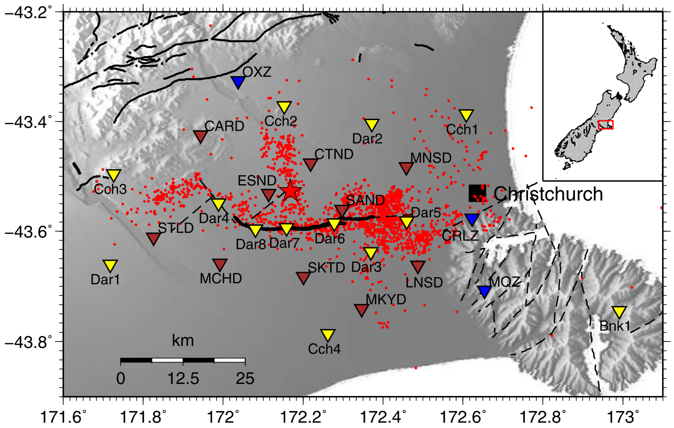

Fig. 1. Map of study area/aftershock sequence. Inset shows relative location. Aftershock locations marked with red circles. Solid black lines show mapped faults from GNS active fault database. Solid black line in the center is the Greendale Fault, mapped by Quigley et al. (2010). Dashed black lines are faults inferred from GPS data by Beavan et al. (2010, 2012) and field observation (Ring and Hampton, 2012 and references therein) respectively. Colored triangles represent Victoria University of Wellington, University of Wisconsin–Madison and University of Auckland broadband temporary stations (yellow), GNS Science short-period temporary stations (brown) and GeoNet permanent stations (blue). Red star marks Darfield earthquake epicenter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

rupture, revealing a previously unknown fault, later named the Greendale Fault (Quigley et al., 2010). The Greendale Fault is predominantly a right-lateral strike–slip fault and produced an average slip of 2.5 m and a maximum of 5 m in the 2010 earthquake (Quigley et al., 2010). The Darfield (Canterbury) earthquake was the first earthquake to have produced a ground surface rupture in New Zealand since the $M_w = 6.5$ earthquake of Edgecumbe in 1987 (Anderson and Webb, 1989). The Darfield (Canterbury) earthquake caused extensive liquefaction, resulting in billions of dollars of damage to residences and services throughout the region (Cubrinovski et al., 2010). The $M_w = 6.2$ Christchurch aftershock on 22 February 2011 caused further destruction and the loss of 185 lives (Bannister and Gledhill, 2012; Kaiser et al., 2012). From here on, the Darfield (Canterbury) earthquake will be referred to as the Darfield earthquake.

1.2. *Data set*

Following the Darfield earthquake, researchers from Victoria University of Wellington, the University of Auckland and the University of Wisconsin–Madison deployed a temporary network of 13 broadband seismometers in the epicentral area (with some along the Greendale Fault trace). That network recorded aftershocks between 9 September 2010 and 13 January 2011. The data set was augmented by data from a 10-station deployment by GNS Science from 8 September 2010 to 29 September 2010 and by data from three permanent GeoNet stations in the region from 8 September 2010 to 11 April 2011 (Fig. 1). Unless otherwise stated, all times are in UTC format.

1.3. *Geological, tectonic, and seismological setting*

The Greendale Fault is located on the Canterbury Plains of New Zealand's South Island. The Canterbury Plains are primarily made up of coalesced flood plains (Forsyth et al., 2008) overlying Paleozoic and Mesozoic greywacke and schist (Cook et al., 1989). Canterbury was considered a region of low seismic hazard before the Darfield earthquake compared to the rest of New Zealand (Stirling et al., 2010), although studies prior to the Darfield earthquake had revealed faults in the northwest Canterbury Plains (Dorn et al., 2010). Post-earthquake studies have found historic evidence for other significant earthquakes in the Canterbury region (Downes and Yetton, 2012). Prior to the Darfield earthquake, a seismic reflection survey of Pegasus Bay northeast of Christchurch (Barnes, 2011) revealed a number of active and inactive offshore faults in the area. E–W striking normal faults formed in the Late Cretaceous have been identified from seismic and gravity studies in the areas surrounding the Greendale Fault (Ghisetti and Sibson, 2012; Jongens et al., 2012, and references therein). Geodetic and seismic inversions (Beavan et al., 2010, 2012) and high-resolution earthquake locations (Syracuse et al., 2012, 2013) indicate the presence of buried fault segments surrounding the surface expression of the Greendale Fault.

The maximum horizontal compressive stress orientation (S_{Hmax}) in the South Island has been found to be 110–120° in the Central Southern Alps (Leitner et al., 2001); 115 ± 16° in North Canterbury and Marlborough (Balfour et al., 2005); 115 ± 10° along the central Alpine Fault (Boese et al., 2012); and 114 ± 9° from borehole breakouts off the coast of South Canterbury (Sibson et al., 2011). Recent work by Townend et al. (2012) using focal mechanism inversions found that this highly uniform S_{Hmax} azimuth of c. 115° at depths of <25 km spans most of the South Island.

Syracuse et al. (2012) determined shear wave splitting (SWS) parameters using the MFAST method (Savage et al., 2010) and earthquake relocations using the tomoDD algorithm (Zhang and Thurber, 2003) on seismograms from the permanent GeoNet stations and the broadband temporary deployment, observing the following: The majority of aftershocks were outside of the regions of greatest slip; fault and stress-parallel fast directions of anisotropy (ϕ) occurred near the Greendale Fault; and predominantly stress-parallel ϕ occurred in the surrounding area. This suggested that the Greendale Fault was pre-existing and that anisotropy is dominated by stress in the region. Syracuse et al. (2012) also investigated apparent temporal changes in SWS parameters and concluded that the changes were caused by spatial variation in anisotropy combined with temporal variation of seismicity, rather than by temporal variations of anisotropy. This study expands on these results by using the data from the additional ten GNS Science temporary stations to produce new SWS measurements for these station-event raypaths and new location estimates using data from all 26 stations with an alternate location algorithm (NonLinLoc, Lomax, 2007).

1.4. *Stress orientation and stress drop*

Sibson et al. (2011) concluded that the Greendale Fault is either a new fault that formed at 30° to the maximum compressive stress orientation (S_1), consistent with Andersonian fault mechanics (Anderson, 1951), or that it was a pre-existing, frictionally strong fault that was optimally aligned with S_1 for reactivation (Sibson, 1985). In the Andersonian framework, strike–slip faults striking at angles to S_1 outside the range of c. 22–30° are interpreted to be frictionally weak; common interpretations of such geometries are that the fault has low frictional strength or high pore fluid pressures (Townend and Zoback, 2001, 2004; Balfour et al., 2005).

Quigley et al. (2012) used fault geometry parameters (length, width, average slip and shear modulus) to obtain an estimate of the static stress drop of the Darfield earthquake of 14 ± 4 MPa. They concluded that such a large stress drop indicated a significant accumulation of stress before failure and that the Greendale Fault was thus frictionally strong. Fry and Gerstenberger (2011) reached the same conclusion based on their high seismologically determined apparent stress estimate of c. 16 MPa.

Local variations in the stress field could occur when the local stress is large enough to rotate the regional stress (Zoback,