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Using regional moment tensors to constrain the kinematics and stress evolution of the 2010–2013 Canterbury earthquake sequence, South Island, New Zealand

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ABSTRACT

On September 3, 2010, a M_W 7.0 (U.S. Geological Survey moment magnitude) earthquake ruptured across the Canterbury Plains in South Island, New Zealand. Since then, New Zealand GNS Science has recorded over 10,000 aftershocks M_L 2.0 and larger, including three destructive ~M_W 6.0 earthquakes near Christchurch. We treat the Canterbury earthquake sequence as an intraplate earthquake sequence, and compare its kinematics to an Andersonian model for fault slip in a uniform stress field. We determined moment magnitudes and double couple solutions for 150 earthquakes having M_W 3.7 and larger through the use of a waveform inversion technique using data from broadband seismic stations on South Island, New Zealand. The majority (126) of these double couple solutions have strike-slip focal mechanisms, with right-lateral slip on ENE fault planes or equivalently left-lateral slip on SSE fault planes. The remaining focal mechanisms indicate reverse faulting, except for two normal faulting events. The strike-slip segments have compatible orientations for slip in a stress field with a horizontal σ_1 oriented ~N115°E, and horizontal σ_3. The preference for right lateral strike-slip earthquakes suggests that these structures are inherited from previous stages of deformation. Reverse slip is interpreted to have occurred on previously existing structures in regions with an absence of existing structures optimally oriented for strike-slip deformation. Despite the variations in slip direction and faulting style, most aftershocks had nearly the same P-axis orientation, consistent with the regional σ_1. There is no evidence for significant changes in these stress orientations throughout the Canterbury earthquake sequence.

1. Introduction[1]

On September 3, 2010 at 16:35 UTC, a M_W 7.0 earthquake (U.S. Geological Survey (USGS) moment magnitude; M_W 7.1, Gledhill et al., 2011) occurred near the town of Darfield in east-central South Island, New Zealand, generating a 30 km long E–W surface rupture and doing substantial damage to the nearby city of Christchurch and vicinity (Fig. 1). Significant aftershock activity lasted over two years, with M 4.0+ events occurring as recently as September and November 2013, and the aftershock footprint extended over 100 km, from the Rakaia River in the west to offshore east of Christchurch. Included in the sequence are four major aftershocks (all ~M_W 6.0) near Christchurch that caused additional severe shaking and liquefaction damage in the city. These earthquakes occurred on previously undocumented structures in the Canterbury Plains, a region of low topographic relief with no evidence of active tectonic features (Fig. 1). This is in sharp contrast to the more typical earthquake behavior in South Island, New Zealand, where the major plate boundary fault regions (the right lateral strike-slip Marlborough fault zone in the north, and the right lateral transpressive Alpine Fault in the west) accommodate most of the current deformation and seismicity, and show significant uplift and large offsets (Fig. 1). Although the Canterbury Plains lie only ~100 km from the Australia–Pacific plate boundary, the region may be more appropriately described as intraplate: it is deforming at low strain rates (16 nstrain/yr of maximum compression; Wallace et al., 2007) compared to the plate boundary faults in the South Island (1–2 orders of magnitude larger strain rates; Beavan et al., 1999, 2002), and seismicity was relatively diffuse and sparse before the M_W 7.0 main shock rupture, rather than concentrating in a narrow zone around a primary fault structure. In the 70 years that GNS Science recorded earthquakes prior to September 3, 2010, the largest event in the Canterbury Plains was M_L 4.9 (GNS Science local Richter magnitude), and smaller events did not cluster or reveal any hidden subsurface faults capable of hosting large earthquakes (Fig. 1).

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[1] We refer to three different magnitudes for earthquakes in this sequence: M_L refers to the GNS Science Richter magnitude, M_W refers to the USGS moment magnitude, and M_W^{RMT} refers to our moment magnitude.

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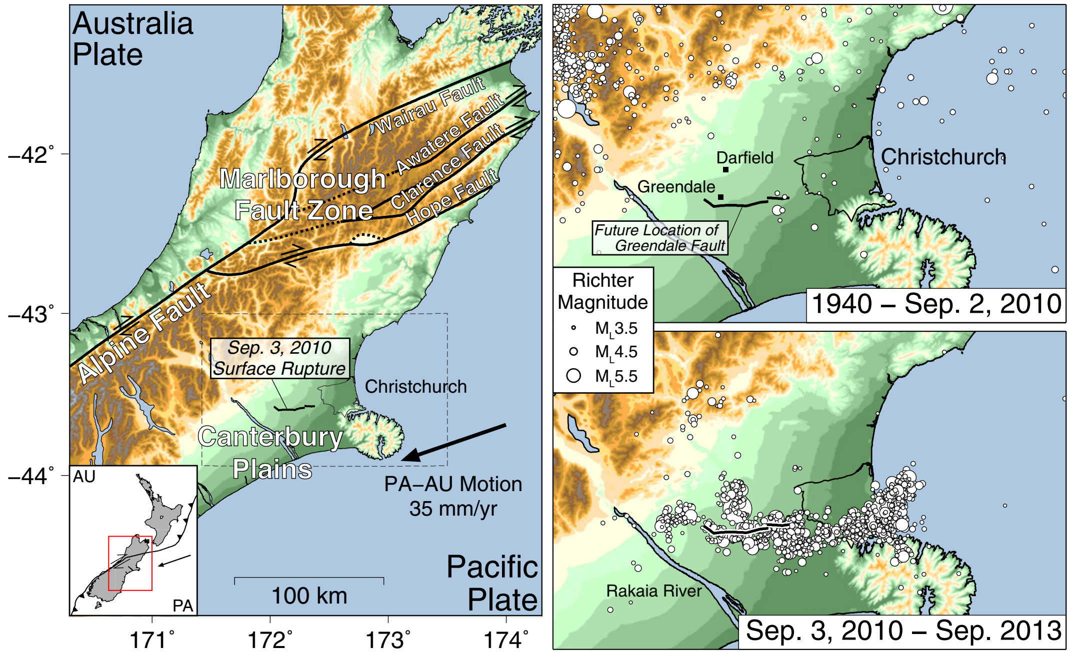

Fig. 1. (Left) Inset: New Zealand straddles the Australia–Pacific plate boundary, which crosses the South Island as a transform/transpressional boundary. The area inside the red box is enlarged to show the tectonic setting of northern South Island, including the Canterbury Plains, and the location of the September 3, 2010 M_W 7.0 main shock. Seismicity in South Island, New Zealand is historically limited to the plate boundary and mountainous zones near the Alpine and Marlborough faults, whereas the Canterbury Plains are conspicuously silent. (Right top) Historical earthquakes larger than M_L 3.0 in the Canterbury Plains from 1940 to September 2, 2010. The largest earthquake in the 70 years prior to 2010 was M_L 4.9. (Right bottom) Earthquakes larger than M_L 3.0 following the September 3, 2010 main shock. This includes five events M_L 6.0 and larger. All seismicity comes from the GNS Science earthquake catalog.

The main shock also had a large stress drop (~16 MPa; Fry and Gerstenberger, 2011) and a fault length–seismic moment ratio (~45 km long, $M_0 \approx 3.5 \times 10^{19}$ Nm) more consistent with intraplate earthquakes than plate boundary events (e.g. Scholz et al., 1986). In this study, we determine source parameters for 150 events in the Canterbury earthquake sequence to constrain its deformation kinematics and stress evolution. These results suggest that seismotectonic models and corresponding seismic hazard models derived for plate boundary settings may not be simply and directly applicable in intraplate settings like the Canterbury Plains.

1.1. Overview of Canterbury sequence seismicity

The earthquakes in the Canterbury sequence (Fig. 2) are shallow crustal events, all less than 20 km deep from GNS Science network locations, within the Rakaia Terrane (Permian to Late Triassic greywacke or its metamorphosed equivalent). The Rakaia Terrane makes up the basement beneath the Canterbury Plains and contains extensive folds and faults from its development in an accretionary wedge during late Paleozoic and early Mesozoic westward subduction beneath Gondwana (Mortimer, 2004), as well as E–W to NE–SW striking normal faults formed during Late Cretaceous extension (Jongens et al., 2012). Capping the Rakaia Terrane is a 1 km thick Late Cretaceous to early Tertiary alluvial sequence including unconformably deposited conglomerate and sandstone, covered by approximately 500 m of unconsolidated Pleistocene alternating glacial and alluvial sediments (Brown and Weeber, 1992). These capping layers hide potentially seismogenic faults in the basement rock and obscure evidence of past surface-rupturing earthquakes. Of the earthquakes in the sequence, only the September 3, 2010 main shock ruptured to the surface through these capping sediments, providing an observable surface rupture (Quigley et al., 2012).

The Canterbury earthquake sequence began with the M_W 7.0 earthquake at 16:35 UTC on September 3, 2010 (04:35 September 4, 2010, local time). Although its epicenter was located less than 5 km south of the town of Darfield, its dominant moment release occurred ~5 km farther south of the epicenter as an E–W right lateral strike-slip fault, near the town of Greendale (Figs. 1 and 2): seismological analysis of the regional coseismic ground motion suggests that the earliest rupture stage involved reverse faulting, with a moment magnitude less than M_W 6.5 (Gledhill et al., 2011). On the other hand, the USGS Wphase and CMT (Hayes et al., 2009, http://earthquake.usgs.gov), and the Global Centroid Moment Tensor project (Dziewonski et al., 1981, http://www.globalcmt.org) solutions indicate dominantly right lateral slip on an east-striking, vertically dipping plane, with no oblique or thrusting component. Near-field geodetic analysis of static offsets generated by coseismic and postseismic slip suggests a more complex and segmented rupture, including a primary E–W right lateral segment, NE–SW reverse segments to the north and west, a N–S left lateral segment to the north, and an E–W right lateral segment with a small amount of subsurface slip east of the main segment (Atzori et al., 2012; Beavan et al., 2012; Elliott et al., 2012). The temporal evolution of the rupture was determined in finite fault solutions; although most of these solutions only model the rupture on the dominant right lateral segment, they do account for nearly the total moment release (e.g. Beavan et al., 2012; Hayes, 2010).

An east-trending surface rupture with right-lateral slip was mapped for approximately 30 km, defined by several main segments (Quigley et al., 2012). Displacement along the surface rupture was dominantly horizontal and right lateral (average ~2.5 m), with small amounts of vertical slip (less than 1 m) that varied along strike. Quigley et al. (2012) divided the September 3, 2010 surface rupture into three segments: a western segment, oriented NW–SE with ~1 m of horizontal slip; a central segment, oriented E–W with horizontal displacements that increased from ~3 m in its western half to a maximum of ~5 m in its eastern half; and an eastern segment, oriented E–W and including several left-stepping en echelon segments, with right lateral displacements of ~1 m. In the western and central segments, vertical displacements were south side up, whereas in the eastern segment, vertical displacements were dominantly north side up. Although the surface rupture terminated ~20 km west of Christchurch, teleseismic finite