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Short communication

Long-period analysis of the 2016 Kaikoura earthquake

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ABSTRACT

The recent $M_w = 7.8$ Kaikoura (New Zealand) earthquake involved a remarkably complex rupture propagating in an intricate network of faults at the transition between the Alpine fault in the South Island and the Kermadec-Tonga subduction zone. We investigate the main features of this complicated rupture process using long-period seismological observations. Apparent Rayleigh-wave moment-rate functions reveal a clear northeastward directivity with an unusually weak rupture initiation during 60 s followed by a major 20 s burst of moment rate. To further explore the rupture process, we perform a Bayesian exploration of multiple point-source parameters in a 3-D Earth model. The results show that the rupture initiated as a small strike-slip rupture and propagated to the northeast, triggering large slip on both strike-slip and thrust faults. The Kaikoura earthquake is thus a rare instance in which slip on intraplate faults trigger extensive interplate thrust faulting. This clearly outlines the importance of accounting for secondary faults when assessing seismic and tsunami hazard in subduction zones.

1. Introduction

On November 13, 2016, a large earthquake struck the northeast coast of the South Island in New Zealand (GeoNet hypocenter: latitude = −42.69°, longitude = 173.02°, depth = 14 km, O.T. =11:02:56 UTC; Global CMT $M_w = 7.8$). This earthquake occurred in the Marlborough Fault system, an intricate network of right lateral strike-slip faults connecting the Alpine fault in the South Island to the Hikurangi subduction zone (cf., Fig. 1). A tsunami swept onto the coastlines with wave-heights of 2.5 m at Kaikoura (https://www.geonet.org.nz/tsunami). This earthquake is the largest event in the region since a magnitude 7.5 earthquake that occured 100 km to the northeast in October 1848 (Grapes et al., 1998; Mason and Little, 2006). The 1848 earthquake ruptured ~100 km of the Awatere Fault near Blenheim with horizontal displacements as large as 6 m causing significant damages in Wellington and the Awatere valley.

Several facts indicate that the 2016 Kaikoura earthquake involved a complex rupture. Long-period moment tensor solutions indicate an oblique thrust focal mechanism with a large non-double couple component. Using the definition of Hara et al. (1996), the non-double couple component of Global CMT (GCMT) and USGS W-phase solutions are $\epsilon = -0.12$ and $\epsilon = -0.21$ respectively. This suggest that the mainshock is not well represented by a single fault plane. Both GCMT and W-phase solutions have large centroid time-delay $\tau_c \sim 57$ s that indicate an anomalously long rupture duration, more than 2.5 times longer than what is expected from standard scaling laws (Duputel et al., 2013). In addition, preliminary fields reports indicate that multiple faults were involved with surface strike-slip offsets as large as 10 m across the Kekerengu fault and coastal uplift between 2 and 5 m northeast of Kaikoura (Litchfield et al., 2016).

In this study, we investigate the mainshock rupture using long-period records available at teleseismic distances. Using this dataset, we conduct a directivity analysis using apparent moment rate functions and perform a multiple-point-source inversion accounting for 3-D Earth structures.

2. Rayleigh-wave moment rate functions

To study the time-history of the rupture and investigate possible directivity effects visible at long-period for the $M_w = 7.8$ Kaikoura earthquake, we compute apparent Rayleigh-wave moment rate functions (MRFs). The dispersive wave-propagation effects are removed by deconvolving the data by point-source synthetic seismograms. To reduce biases in Rayleigh-wave MRFs due to unaccounted lateral heterogeneities, we use broadband (10–600 s) SEM synthetics computed for a 3D Earth model (S362ANI and CRUST2.0) using the spectral element code SPECFEM3D_GLOBE (Komatitsch and Tromp, 2002). Deconvolution is performed using the projected Landweber deconvolution method (Bertero et al., 1999; Lanza et al., 1999) imposing causality and positivity (Duputel et al., 2016).

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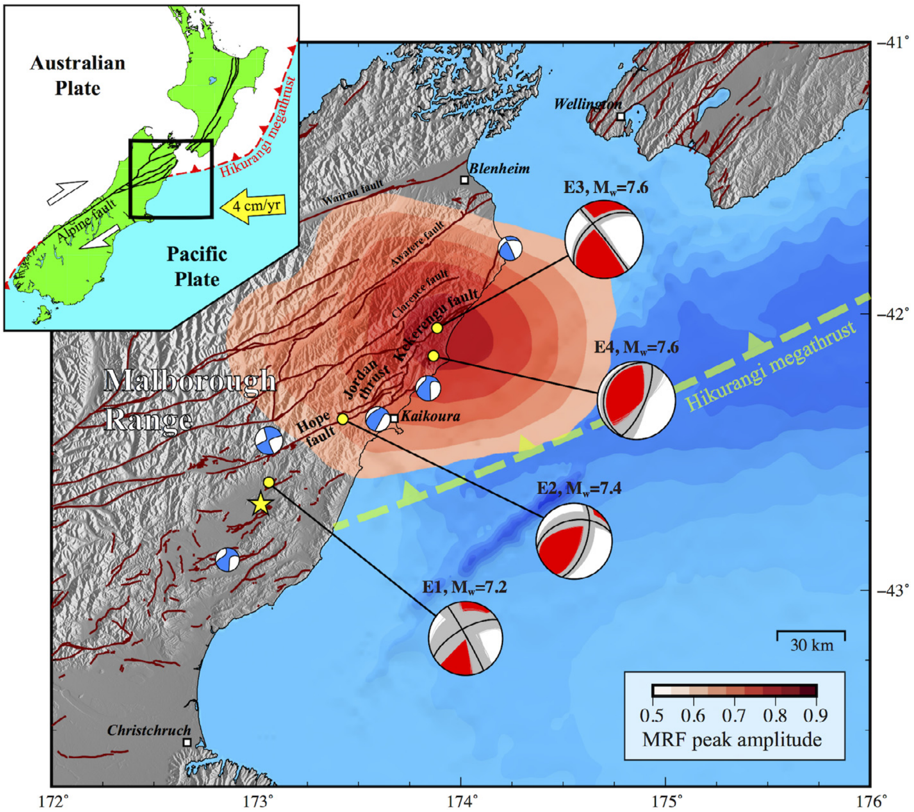

Fig. 1. The 2016 Kaikoura earthquake sequence. Red mechanisms correspond to our preferred four-point-source model obtained using body waves and surface waves assuming a 3-D Earth model. Red colors indicate peak-stacked amplitude in the source region from moment rate functions (MRF) backprojected relative to the main shock epicentral location. Blue mechanisms are the Global CMT solutions obtained for $M_w \geqslant 5$ aftershocks (2016/11/14 to 2016/11/22). Red lines are faults traces from the New Zealand Active Faults Database (GNS Science, https://data.gns.cri.nz/af). Yellow dashed line shows the approximate trench location of the Hikurangi megathrust. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The MRFs shown in Fig. 2 indicate an unusual initiation with very small moment rate in the first 60 s. Following this slow initiation phase, the moment rate rises abruptly during ~20 s. This main energy burst shows clear azimuth-dependent time-shifts that are consistent with unilateral rupture propagation to the northeast. Such directivity is in agreement with both GCMT and W-phase centroid location that lie ~120 km northeast of the epicenter. To study this apparent directivity, we image the spatial distribution of long-period seismic wave radiation. To do so, the MRFs are averaged in 10° azimuthal windows and back-projected over a gridded region around the epicenter assuming an average phase-velocity of 4 km/s. The resulting peak stacked amplitude shown in Fig. 1 indicates that this main moment-rate burst emanated from a region including the Kekerengu fault and the east coast of the upper South Island.

3. Multiple point source analysis of the 2016 Kaikoura earthquake

3.1. Multiple CMT inversion approach

We employ a strategy similar to Duputel et al. (2012) where multiple moment tensor sources are inverted simultaneously using W-phase waveforms. Here, we extend this approach to surface waves using a larger time-window in the period range of 100–450 s. The W-phase being mainly sensitive to first-order source parameters, incorporating surface waves and extending our passband to shorter periods improve our ability to capture more details of the rupture process. While most of the W-phase energy propagates into the mantle and are therefore not strongly affected by shallow structures, fundamental mode surface waves are sensitive

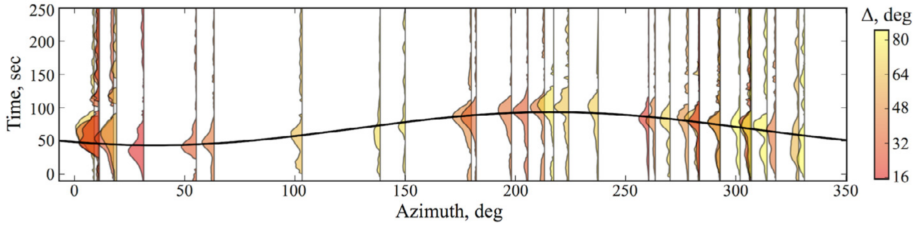

Fig. 2. Rayleigh-wave moment rate functions. Apparent moment rate functions (MRFs) are shown as a function of azimuth and colored by epicentral distance. These represent seismic moment as a function of time observed at different stations. The black curve corresponds to the maximum MRF peak amplitude, showing the predicted arrival time of energy radiated from this location (cf., Fig. 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)