Multiple-Fault, Slow Rupture of the 2016 $M_w$ 7.8 Kaikoura, New Zealand, Earthquake: Complementary Insights from Teleseismic and Geodetic Data

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Abstract We investigate the complex rupture properties of the 2016 $M_w$ 7.8 Kaikoura earthquake by jointly inverting teleseismic body-wave and regional Global Positioning System (GPS) coseismic deformation data within a multifault model. We validate our results by forward modeling recorded Interferometric Synthetic Aperture Radar (InSAR) interferograms. Our study reveals the complementary depth-dependent contributions of teleseismic and local geodetic data to the cumulative slip distribution. The resulting joint inversion model of the rupture process and slip pattern explains both the far-field (teleseismic data) and near-field (GPS and InSAR data) observations. The model highlights variable rupture velocity throughout the sequence, with an initial high-velocity (2.25 km/s) pulse followed by slow (~1.5 km/s) yet significant reverse and transverse motion on faults stretching at least 160 km to the north of the origin. We map significant thrust motion on a dipping plane representing the combined effects of the Hope, Hundalee, and Jordan thrust faults as well as large strike-slip motion along the Kekerengu and Needles faults. The mainshock also ruptured the deep portion of the subduction interface at a velocity of 1.0 km/s.

Introduction

On 13 November 2016, the $M_w$ 7.8 Kaikoura earthquake struck the northeastern coast of the upper South Island, New Zealand. The epicenter determined by New Zealand’s geological hazard monitoring center (GeoNet) was at 42.69° S, 173.02° E, with a focal depth of 15 km (Fig. 1). The earthquake caused widespread strong ground motion, generating numerous landslides and damage to the built environment. Fortunately, it occurred in a sparsely populated area, limiting its societal impact. The earthquake also generated tsunami waves up to >5 m along the Kaikoura coast. The mainshock occurred in the tectonically active and structurally complex plate boundary between the Pacific and Australian plates. The region marks the transition between the Hikurangi subduction zone to the north and the transpressional dextral Alpine fault to the south.

According to the Global Centroid Moment Tensor (CMT) solution (strike 219°, dip 38°, rake 128°; see Data and Resources), the strike is consistent with the regional geological structures, however, the dip angle is much shallower than the dip angles of the faults previously mapped in the region (Litchfield et al., 2014, 2016). In addition, the Global CMT solution suggests an oblique thrust-faulting mechanism with a significant non-double-couple component of 43% and large centroid time delays of about 58 s from the $W$-phase solution, indicating that the 2016 Kaikoura mainshock cannot be well represented by a single point source and may involve multiple rupture planes or slip vector variations. Multifault rupture is evident in the geodetic and field observations. These data show that at least 12 faults, possibly including the southern Hikurangi subduction interface, were involved in the mainshock sequence and extend from the hypocenter in the south with the rupture length of ~170 km northeastward to the Kekerengu fault (Litchfield et al., 2016; Hamling et al., 2017; Kaiser et al., 2017).

Several studies suggest that this complex earthquake involved rupture of both upper crustal faults and the subduction megathrust (e.g., Bai et al., 2017; Duputel and Rivera, 2017; Hamling et al., 2017). Previous studies have demonstrated the weaknesses of investigating the source properties of large earthquakes with a single type of data (Wen and Ma, 2010; Wen et al., 2012). Source models resulting from previous studies of the Kaikoura earthquake that utilized individual datasets (e.g., local geodesy, regional strong motion, or teleseismic long-period [LP] seismic data) have in many cases been incompatible with one another; studies based on local and regional data generally map most source deformation to crustal faults (e.g., Hamling et al., 2017; Kaiser et al., 2017) whereas those based on teleseismic data attribute most deformation to a megathrust-like source (e.g., Bai et al., 2017). On
the other hand, Cesca et al. (2017) and Wang et al. (2018) proposed a model by jointly inverting Global Positioning System (GPS), Interferometric Synthetic Aperture Radar (InSAR), strong-motion, and teleseismic data. The 2016 Kaikoura earthquake was well recorded by global teleseismic stations. Teleseismic data typically have high signal-to-noise ratios and widespread azimuthal coverage. Thus, they are frequently used to investigate the primary characteristics of fault rupture behavior and slip pattern. However, both their LP nature limit their sensitivity to small-scale complexities of the rupture process. Conversely, the static nature of near-field GPS and InSAR coseismic deformation data provides good constraints on the shallow-faulting pattern as well as the total rupture area. These complementary sensitivities allow joint studies of teleseismic and local geodetic data to define rupture models containing both small- and large-scale features. Significantly, using joint inversion techniques, it is also possible to map variations in rupture speed that might not be captured by a single seismic type of dataset in isolation. In this study, we resolve the spatial slip distribution from teleseismic and geodetic data. In addition to invert the spatial slip distribution from individual and joint dataset, we further calculate the synthetic GPS deformation field from our slip model resulting from teleseismic only inversion. We use the difference from this synthetic GPS forward calculation and the observed GPS measurements to decompose the contribution of slip at deep and shallow depths of the fault from the slip models. We examine our preferred model by forward modeling a synthetic InSAR interferogram, which often better constrains broader regional crustal deformation due to the advantage of both its high resolution and wide coverage. We find a good correlation between the synthetic interferograms from our joint inversion result and measured interferograms.

Fault Geometry

Field investigations show that the 2016 Kaikoura mainshock ruptured multiple faults with many short segments, which have various orientations and slip vectors (Litchfield et al., 2016, 2017; Hamling et al., 2017; Kaiser et al., 2017). The multiple point-source model of Duputel and Rivera (2017) suggests a southern strike-slip fault with higher dip angle near the epicenter, and both an oblique thrust as well as a northern strike-slip fault with lower dip angles. Considering the resolution of teleseismic data, we adopt a simplified finite-fault geometry based on the previous studies, the field observations, and aftershock distribution (Litchfield et al., 2016, 2017; Duputel and Rivera, 2017) suggests a southern strike-slip fault with higher dip angle near the epicenter, and both an oblique thrust as well as a northern strike-slip fault with lower dip angles. Considering the resolution of teleseismic data, we adopt a simplified finite-fault geometry based on the previous studies, the field observations, and aftershock distribution (Litchfield et al., 2016, 2017; Duputel and Rivera, 2017; Hamling et al., 2017; Kaiser et al., 2017). Therefore, as shown in Figure 1, two fault segments are set to correspond to the main geological structure with large surface offsets (Litchfield et al., 2016, 2017; Hamling et al., 2017; Kaiser et al., 2017). The first segment (F1), which was slightly adjusted from the strong-motion analysis (Kaiser et al., 2017) to represent the rupture initiation on the Humps fault, is an 80-km southern segment oriented N236°E with a 45-km width (i.e., down-dip extent) dipping 61°. Both the far-field and near-field seismic data (Duputel and Rivera, 2017; Kaiser et al., 2017) suggest oblique faulting with a dip of 49° on the northern part, which is consistent with the field observations (Litchfield et al., 2017). Although the dip angle of the Needles fault is high, the coseismic offsets were much smaller than that of the Jordan thrust and Kekerengu faults. Thus, the second segment (F2) is represented as a 160-km northern segment oriented N225°E with a 55-km width dipping 49° to generally represent the main energy released on the Jordan thrust and Kekerengu faults. In addition, several studies show that the 2016 Kaikoura earthquake released seismic moment on the subduction plate interface during the faulting (e.g., Bai et al., 2017; Duputel and Rivera, 2017; Hamling et al., 2017; Wang et al., 2017).
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et al., 2018). Based on the aftershock distribution (Fig. 1) and tectonic setting of the Hikurangi subduction margin (Wallace and Beavan, 2010), the third segment (F3) represents the shallow-dipping rupture required by the LP seismic data (Global CMT solution; Duputel and Rivera, 2017) and is defined as a 60-km segment oriented N196°E with a 60-km width dipping 17°.

Data and Methods

We use teleseismic broadband waveforms for 16 P waves and 8 SH waves from the Incorporated Research Institutions for Seismology Data Management Center stations with epicentral distances between 30° and 90° for the finite-fault modeling, which shows a good azimuthal coverage of the earthquake (Fig. 2). We integrate the velocity records to generate displacement seismograms after removing the instrument response from the original velocity waveforms and band-pass filtering the data between 0.01 and 0.5 Hz. Teleseismic Green’s functions were computed with the generalized ray theory method (Langston and Helmberger, 1975) using the 1D crustal velocity structure of CRUST 2.0 (Bassin et al., 2000). To model the earthquake rupture process, we consider waveforms from 10 s before to 130 s after the P- and S-wave arrivals, with a sampling rate of 0.2 s.

Many continuous and campaign GPS stations recorded coseismic offsets resulting from the earthquake (Hamling et al., 2017). We simulate three-component static ground displacements using the finite-fault approach of Ji et al. (2002), with a regional 1D velocity structure modified from Eberhart-Phillips and Bannister (2010) and Fry et al. (2014). We invert coseismic offsets from 76 GPS stations within the study area (Fig. 1). In addition, we calculate the static ground displacements within the study area at every node of a 2 × 2 km grid to test our model against measured InSAR interferograms.

For a given seismic station, the displacement record can be represented as the linear sum of slip contributed from each ruptured subfault. Therefore, the observed and synthetic waveforms can be expressed as a system of linear equations:

\[
\begin{align*}
\begin{bmatrix}
&w_1 \\
&w_2 \\
&\vdots \\
&w_p
\end{bmatrix} A
\begin{bmatrix}
&x_1 \\
&x_2 \\
&\vdots \\
&x_s
\end{bmatrix} &=
\begin{bmatrix}
&w_1 \\
&w_2 \\
&\vdots \\
&w_p
\end{bmatrix} b
\end{align*}
\]

(1)

(Lee et al., 2013), in which A represents the matrix of Green’s functions of teleseismic waveforms and static ground displacements, b is the vector of observed data, and x is the solution matrix of the subfault dislocations. To ensure appropriate contributions from the different datasets with different units and numbers of data points, we normalize the weight according to the following equations:

\[
\epsilon = (wA x - w b)^2 / (w b)^2.
\]

(2)

For each subfault, we solve for rake direction and use a triangular source time function with a width of 4 s. Several studies indicate that the rupture velocity of the 2016 Kaikoura earthquake might vary during faulting (Bai et al., 2017; Hollingsworth et al., 2017; Kaiser et al., 2017), therefore, we explore a wide range of rupture velocities during the teleseismic waveform inversion systematically varying rupture velocity between 1.0 and 3.0 km/s on each segment, with an increment interval of 0.25 km/s. In total, this leads to 729 inverted slip models with various rupture velocities. The multiple-time-window analysis, allowing each subfault to slip in several time windows (e.g., triangular source time functions) following the passage of the rupture front, is useful to permit more flexibility in modeling the rupture of large earthquakes with longer slip duration (Hartzell and Heaton, 1983). As mentioned in Lay et al. (2010) and Wen et al. (2012), positioning of slip is mainly dominated by the rupture velocity imposed, and the use of multiple time windows does not improve resolution of the variation of rupture velocity during faulting. Hence, we use a simple single-time-window modeling scheme to save computation time during inversion for the rupture speed examination.

Because the kinematic models are nonunique, they require further information as the constraint. Several studies have shown that the main energy release is between 60 and 80 s after the initiation (e.g., Bai et al., 2017; Cesca et al., 2017; Duputel and Rivera, 2017; Zhang et al., 2017). High-
rate GPS data record this dominant displacement pulse on stations located in the northern half of the rupture (Kaiser et al., 2017). On the other hand, the location of the main moment-rate burst backprojected from Rayleigh-wave data (Duputel and Rivera, 2017) is similar with the model derived from geodetic data (Hamling et al., 2017) and is located near 42° S. Therefore, we limit the rupture front propagation through this region to between 60 and 80 s after the initiation, and we also apply a seismic moment constraint, based on the Global CMT solution, in the inversion.

Results

To compare the information about the source process derived from various data, we carry out three inversion procedures: (1) fitting only teleseismic waveforms, (2) fitting only GPS offsets, and (3) fitting both teleseismic and GPS data. For the inversions fitting only teleseismic data, the optimal model with a misfit of $\varepsilon = 0.417$ indicates that the 2016 Kaikoura earthquake initially ruptured with a velocity of 2.0 km/s in segment F1, followed by 1.75 km/s in segment F2, and propagated to segment F3 with a very slow velocity of 1.0 km/s. This slow rupture speed is somewhat compatible with backprojection analysis of Hollingsworth et al. (2017), which suggests rupture velocities were in 1.5–2.5 km/s range. We apply a multiple-time-window modeling scheme with the derived optimum rupture velocity variation using eight 4-s duration triangles lagged by 2 s each, for maximum subfault rupture durations of 18 s. The slip model with $\varepsilon = 0.340$ and comparison of modeled and observed waveforms are shown in Figure 3. The total seismic moment

Figure 3. Slip model from the teleseismic waveform inversion and comparison of the observed (solid line) and the synthetic (dashed line) waveforms. Stars show the initiation locations on each segment, and arrows and contours indicate the slip vectors and rupture time, respectively. The station name and peak value of the record in micrometers are shown above the waveforms. The number below each segment indicates the percentage of seismic moment released. The color version of this figure is available only in the electronic edition.
is $8.90 \times 10^{20}$ N·m ($M_w$ 7.90). The model exhibits a very weak initiation with relatively little slip in segment F1, and one obvious asperity on segment F2 that ruptured with large amounts of slip at deeper depths, and a generally smoother slip distribution on the subduction interface F3. These features coincide with two large subevents located near 42° S that released energy about 60–80 s after the origin time in the inversion results of Duputel and Rivera (2017). The northern end of F2 displays significant strike-slip motion in the shallow part that may reflect the rupture of the Needles fault.

The inverted model fitting only GPS data (misfit of $\epsilon=0.020$) is shown in Figure 4a. This model is similar to the model derived from geodetic data (Hamling et al., 2017). The rupture sequence began with relatively minor slip-on segment F1, followed by rupture of the main asperity on the shallow part of segment F2, corresponding to the main energy released on the Jordan thrust and Kekerengu faults. Segment F3 ruptured with large amounts of deep reverse slip, which is consistent with the location and faulting mechanism revealed by Duputel and Rivera (2017). The total seismic moment is $8.03 \times 10^{20}$ N·m ($M_w$ 7.87).

The joint inversion best fits the data with relatively slow rupture velocities for F2 and F3. The optimal model (misfit of $\epsilon=0.554$) suggests that the Kaikoura earthquake initially ruptured with a velocity of 2.25 km/s in segment F1, slowed down to 1.50 km/s in segment F2, and then rupture propagated across F3 at 1.0 km/s. The significantly slow velocity in segment F2 is comparable with the average rupture speed of 1.4 km/s estimated from backprojection imaging by Zhang et al. (2017) as well as the average rupture velocity.
of 1.5 km/s derived from the joint inversion by Wang et al. (2018). Figure 5 shows the final slip model and waveform fitting, with a misfit of $\varepsilon = 0.457$, after applying multiple-time-window modeling scheme. This joint inversion model also reveals a weak initiation with little slip in segment F1, however, there is a significant main asperity in segment F2 and a minor asperity in the deeper part of segment F3. The total seismic moment is $9.91 \times 10^{20}$ N·m ($M_w$ 7.93).

Discussion and Conclusions

All of the optimal models from both the joint inversion and the teleseismic-only inversion reveal slow rupture processes during the 2016 Kaikoura earthquake. This is consistent with the result of previous studies (Duputel and Rivera, 2017; Holden et al., 2017; Kaiser et al., 2017; Wang et al., 2018; Zhang et al., 2017). However, because of the limited resolution of teleseismic data and the simplified fault geometries, models derived purely from teleseismic data can provide the primary source time process and slip pattern, especially at greater depths, but lack the resolution to reveal slip patterns at shallow depths. On the other hand, the geodetic data can better constrain the slip pattern at shallow depths, yet are relatively insensitive to deeper kinematics and contain no timing or rupture velocity information. Both our teleseismic-only model and those derived from seismic data (Hollingsworth et al., 2017; Zhang et al., 2017) reveal large amounts of deep slip. Although the locations of dominant energy released in segments F2 and F3 (Fig. 3) are consistent with the main moment-rate burst backprojected from the Rayleigh-wave data (Duputel and Rivera, 2017), the synthetic surface displacements do not fit the observations. Figure 6a shows the
synthetic static ground displacements derived from the teleseismic waveform inversion model (Fig. 3). Although the orientations of synthetic displacement are mostly consistent with the GPS observations, the synthetic displacement underestimates the measured displacement. Figure 6b shows the synthetic static ground displacement derived from the GPS offset inversion model (Fig. 4a). With the exception of some near-fault stations, the synthetic coseismic displacements well reproduced the amplitude and orientation of the observations for both amplitude and orientation. Figure 6c shows the synthetic static ground displacements derived from the joint inversion model (Fig. 5). The synthetic coseismic displacements still exhibit good fits to both amplitude and orientation. To resolve the possible slip distribution at shallower depths, we also calculate the difference between the synthetic GPS from the teleseismic slip model and the observed GPS offsets. Then, we use this difference to invert a slip model (Fig. 4b), which is more sensitive to shallow deformation. Differences in the slip patterns of Figure 4b to 4a (GPS alone) and Figure 3 (teleseismic data alone) suggest that the geodetic data better constrain both slip within depths of 0–20 km and the northern edge of F3, whereas teleseismic data well extract slip at deeper depth and are sensitive to the northern offshore rupture of F2. These general features are consistent with the results shown in Figure 5 of the spatial slip distribution from joint inversion and suggest the reliability of this joint analysis.

We further conducted a forward simulation of synthetic aperture radar (SAR) interferograms (Fig. 7), which were not incorporated in the inversion process. For calculating the displacements of radar line of sight (LOS), average looking vectors (east, north, and up) are used: (−0.6761, 0.2205, and −0.7015) for the descending ALOS-2 interferogram and (0.5986, 0.1923, and −0.7748) for the ascending Sentinel-1A interferogram (data and parameters were provided by Ian J. Hamling). Although our teleseismic waveform inversion model is roughly compatible with results from other seismological studies (Hollingsworth et al., 2017; Zhang et al., 2017), the slip vectors at shallow depths are much smaller than those of the model derived from geodetic data (Hamling et al., 2017), especially near the Kekerengu fault. Therefore, as shown in Figure 7, both the synthetic descending and ascending interferograms derived from the teleseismic waveform inversion model (Fig. 3) fail to reproduce the density of fringes in the SAR observations, which indicates insufficient ground displacements. This points out the difficulty in resolving slip portioning, especially for the shallow slip, using teleseismic waveforms alone. Conversely, both the synthetic descending and ascending interferograms derived from the GPS offset inversion (Fig. 4a) and joint inversion models (Fig. 5) match fringe patterns contained in the observations quite well, except for the near-fault area, as shown in Figure 7. Interestingly, when comparing the LOS residual of different models, the joint inversion model better fits the measured LOS in the western off-fault region. This again suggests the need for slip at deeper depths contributed from the teleseismic data, and the geodetic data providing further constrain on the most near-fault region.

Several studies have shown the complex fault segmentation and large rupture speed variation for this 2016 Kaikoura earthquake (Hamling et al., 2017; Holden et al., 2017; Wang et al., 2018). However, the simplified fault geometries with fixed rupture velocity for each segment limit the exploration of the faulting process. The moment rate functions in Figures 3 and 5 show a longer duration than other studies. This could be expected and is mainly due to the slow and fixed rupture velocity for the long segment F2. Even though, our joint inversion model can explain both
the far-field (teleseismic data) and near-field (GPS and InSAR data) observations and reveal the main rupture properties of the 2016 Kaikoura earthquake.

By integrating the rupture information extracted from the teleseismic data and GPS data, our joint inversion model suggests that the 2016 Kaikoura earthquake ruptured northeastward with a weak initiation, significant thrust motion in the northern part of the Hope and/or Humps and Hundalee faults, large oblique motion along the Kekerengu fault, and some strike-slip displacement on the Needles fault. Several studies show that the 2016 Kaikoura earthquake released seismic moment on the subduction plate interface during the faulting (e.g., Bai et al., 2017; Duputel and Rivera, 2017; Hamling et al., 2017; Wang et al., 2018), whereas some studies model the mainshock rupture process with shallower strike-slip and thrust faults only (Cesca et al., 2017; Holden et al., 2017; Zhang et al., 2017). In our three models (Figs. 3–5), the slip-on segment F3 released 15%–25% of the total seismic moment, and the amounts are much smaller than those of segment F2 (65%–80% of the total seismic moment). Figure 8

Figure 7. (a) Observed, (b) modeled, and (c) residuals of ALOS-2 and Sentinel-1A interferograms from teleseismic waveform inversion, GPS offset inversion, and joint inversion results, respectively. The star shows the epicenter location. LOS, line of sight. The color version of this figure is available only in the electronic edition.
shows the contribution of segment F3 to the seismic records for teleseismic waveform inversion model and joint inversion model, and it mainly explains the minor pulses later than 90 s, which are close to the end of faulting (Bai et al., 2017; Cesca et al., 2017; Duputel and Rivera, 2017; Zhang et al., 2017; Wang et al., 2018). Thus, similar to the conclusion of Holden et al. (2017), most of the faulting process of the 2016 Kaikoura mainshock can be explained by the movement on the crustal faults. However, the contribution from the subduction interface is less, but required, and this is similar to the result of Wang et al. (2018). In comparison with the high-frequency (HF) sources imaged from backprojection analysis of Hollingsworth et al. (2017) and Zhang et al. (2017), our joint inversion revealed the energy release of LP sources. The weak initiation with the highest rupture speed (2.25 km/s) in segment F1 contains relatively large HF radiation. The region with a large asperity with slow rupture velocity (1.5 km/s) in segment F2 lacks HF energy radiation, whereas an HF source was detected near to the rupture front of main asperity of segment F2, mostly south of −42°. The variation of rupture speed and the compensation of the energy release in HF and LP sources describe complex rupture dynamics during the faulting of the 2016 Kaikoura earthquake. During the faulting process, the rupture velocity is strongly related to the strength and stress state of the fault, fault geometry, and the fracture energy (Rosakis, 2002; Kanamori and Rivera, 2006). Complex multifault rupture, such as the 2016 Kaikoura earthquake, requires time for stress transfer from the adjacent faults to reach the critical status of rupture and thus slows down the propagation speed. Numerous slow-slip events have been identified in Hikurangi subduction margin (Wallace and Beavan, 2010), and the 1947 Offshore Poverty Bay tsunami earthquake even ruptured with a very slow speed of 150–300 m/s (Bell et al., 2014). This suggests that the slow rupture velocity during the 2016 Kaikoura earthquake is reasonable and perhaps a fundamental characteristic of the southern Hikurangi megathrust. It also presents a mechanism to generate much of the LP long-duration ground motions observed (Bradley et al., 2017; Kaiser et al., 2017) at local and regional distances. Our results, coupled with evidence of slow rupture elsewhere along the Hikurangi margin, suggest that slow rupture and the resulting increase in tsunami potential and LP ground motion should be considered in future hazard studies in the region.

**Data and Resources**

All data used in this article came from published sources listed in the References section, and all figures were generated using the Generic Mapping Tools v. 4.5.8 (www.soest.hawaii.edu/gmt/, last accessed December 2017; Wessel and Smith, 1998). Global Centroid Moment Tensor (CMT) solution is available at https://earthquake.usgs.gov (last accessed December 2017).

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