The 13 November 2016 Kaikoura, New Zealand earthquake: rupture process and seismotectonic implications

Yi-Ching Lo1, Li Zhao2*, XiWei Xu3, Ji Chen4, and Shu-Huei Hung1
1Department of Geosciences, National Taiwan University, Taipei, Taiwan, China;
2School of Earth and Space Sciences, Peking University, Beijing 100871, China;
3Institute of Crustal Dynamics, China Earthquake Administration, Beijing 100085, China;
4Department of Earth Science, University of California, Santa Barbara, CA, U.S.A.

Abstract: The 13 November 2016 Kaikoura earthquake occurred in the northeastern coastal region of the South Island, New Zealand. The $M_w$ 7.8 mainshock generated a complex pattern of surface ruptures, and was followed within about 12 hours by three moderate shocks of $M_w \geq 6.0$. Here we use teleseismic waveforms to invert for the source rupture of the Kaikoura earthquake. The resulting slip-distribution model exhibits insignificant slip near the hypocenter and three pockets of major slip zones with distinct senses of motion. The mainshock started from a rupture near the hypocenter, grew into thrust on shallow crustal faults ~50 km northeast of the hypocenter, and then developed into two slip zones: a deeper one with oblique thrust and a shallower one with almost purely right-lateral strike-slip. Locations of the thrust and strike-slip motions in the slip-distribution model agree well with reported coastal uplifts and horizontal offsets. The overall slip pattern is dominated by horizontal motion, especially at shallow depth, due to the partitioning of thrust and strike-slip motions above the subduction zone megathrust. Aftershock distribution suggests that most aftershocks tend to occur near the edges of the major slip zones of the mainshock. This observation on aftershock locations may provide useful information for seismic hazard assessments after large earthquakes.

Keywords: slip distribution; Kaikoura earthquake; aftershock distribution; slip partitioning

Citation: Lo, Y.-C., Zhao, L., Xu, X. W., Chen, J., and Hung, S.-H. (2018). The 13 November 2016 Kaikoura, New Zealand earthquake: rupture process and seismotectonic implications. Earth Planet. Phys., 2, 139–149. http://doi.org/10.26464/epp2018014

1. Introduction

On November 13, 2016, a strong earthquake shook the Kaikoura region in northeastern South Island, New Zealand. The event had a magnitude of $M_w = 7.8$ and a shallow hypocenter depth of 15.1 km (USGS, https://earthquake.usgs.gov/earthquakes/eventpage/us1000778i#executive). The global centroid moment tensor (GCMT, http://www.globalcmt.org/CMTsearch.html) solution indicates that the focal mechanism is a mixture of thrust and strike-slip motions. The mainshock was followed by numerous aftershocks including three moderate ones of $M_w \geq 6.0$. The hypocenter of the mainshock was located less than 100 km northeast of Christchurch where a $M_w = 6.3$ earthquake occurred in February 2011 and caused severe fatalities. The shallow depth and large magnitude of the Kaikoura mainshock led to strong ground shaking with two reported deaths (Wikipedia, https://en.wikipedia.org/wiki/2016_Kaikoura_earthquake) and tsunami run-up of up to ~7 m being recorded near Goose Bay, about 17 km northeast of Kaikoura (Power et al., 2017). Field and marine surveys (e.g. GeoNet) and geodetic analyses from InSAR images and GPS measurements following the earthquake revealed ruptures on multiple faults (Hamling et al., 2017; see also Figure 1b of Shi et al., 2017) including the Hope, Humps, Hundalee, Jordan Thrust, Kekerengu, Papatea, and Uwerau faults on land (see Figure 1a for fault locations), as well as the Needles Fault offshore northeast of the South Island. The senses of slip are all right-lateral on the Hope, Humps, Hundalee, Kekerengu and Needles faults, while mostly oblique-reverse on the Jordan Thrust and Papatea faults (e.g. Hamling et al., 2017).

Tectonically, the complex multiple ruptures of the Kaikoura earthquake occurred on the northern extension of the Alpine Fault, an oblique right-lateral strike-slip fault along the Australia-Pacific plate boundary system (Figure 1b). Northeast of the Alpine Fault, the Pacific Plate subducts westward under the Australian Plate along the northeast-trending Hikurangi Trench with a horizontal convergence rate of 40–45 mm/a; while to the south the Australian Plate plunges eastward under the Pacific Plate along the Puysegur Trench at a rate of ~38 mm/a (Anderson & Webb, 1994; Gledhill et al., 2011; Litchfield et al., 2014). Thus, the Alpine Fault is a transform fault providing a double bending linkage between the Hikurangi Trench in the north and the Puysegur Trench in the south. Generally speaking, the Alpine Fault slips in a right-lateral sense at an average rate of 29±2 mm/a with a single fault-trace and a minor amount of vertical slip (e.g. Barnes 2009; Langridge et
al., 2010, 2014), whereas its northern part splits into a series of northeast-trending faults including mainly, from south to north, the Hope Fault, the Clarence Fault, the Awatere Fault, and the Wairau Fault (Figure 1a).

Collectively known as the Marlborough Fault System (MFS), these faults are mostly strike-slip at slower Holocene rates (i.e. 3–6 mm/a) in the northern South Island, and they effectively transfer the oblique plate convergence with a relatively high rate of 35–40 mm/a between the Alpine Fault and Hikurangi Trench (Little and Jones, 1998; Barnes, 2009; Langridge et al., 2010, 2014), leading to one of the most seismically active regions in the world. Since 1900, there have been 15 earthquakes of $M > 7.5$ in the convergence zone across the South and North islands and to the west of the plate boundary (USGS, https://earthquake.usgs.gov/earthquakes/eventpage/us1000778i#region-info). The 2016 Kaikoura mainshock and its moderate aftershocks are located within this transform linkage. The complicated active fault setting may have

Lo Y-C et al.: Slip distribution of 2016 Kaikoura earthquake
played a critical role in the extraordinary complexity of the Kaikoura earthquake sequence, resulting in the most complex surface rupture pattern ever recorded on land (e.g. Bradley et al., 2017; Hamling et al., 2017). This pattern may help us understand the unique dynamic triggering of the rupture process of the Kaikoura earthquake (Hollingsworth et al., 2017).

In this study, we use broadband teleseismic waveforms to invert for the source slip distributions of the Kaikoura mainshock and one of its moderate aftershocks ($M_w$ 6.5). Although field surveys of surface ruptures as well as geodetic and InSAR observations of ground deformation indicate that the Kaikoura mainshock involved ruptures on multiple faults (e.g. Zhang et al., 2017; Bradley et al., 2017; Cesca et al., 2017; Hamling et al., 2017; Shi et al., 2017; Wang et al., 2018) near the surface, we adopt a single-plane fault model in the inversion of teleseismic waveforms. Our results were validated by bootstrap tests, which demonstrated the robustness of the slip-distribution models. To reconcile different geophysical observations for the Kaikoura mainshock would require a more comprehensive study considering movements on multiple faults, which is beyond the scope of this study. The main objective for teleseismic waveform inversion is to provide a timely first-order description of the overall pattern of the source rupture, in particular the rupture at depth for which seismic data may have a greater level of sensitivity than geodetic and InSAR observations. In the end, the seismological results obtained here are interpreted in the context of the structural geological and tectonic environment to

$$u(r; t) = \sum_{i=1}^{M} \mu_i S_i A_i \left[ \cos(i) G^S_i(r; t; v_i) + \sin(i) G^D_i(r; t; v_i) \right] \dot{h}_i(t; SP_i; EP_i)$$

where $S_i$ and $\lambda_i$ are respectively the amount and rake angle of the slip on the $i$-th subfault with area $A_i$ and rigidity $\mu_i$, $G^S_i(r; t; v_i)$ and $G^D_i(r; t; v_i)$ are the Green’s functions at the station location $r$ caused by unit along-strike and up-dip slips, respectively, on the $i$-th subfault, and $v_i$ is the rupture speed for the subfault. $h_i(t; t_i^{SP}, t_i^{EP})$ is the normalized subfault slip-rate function (Ji et al., 2003) composed of two quarter cosine functions of different periods: one rising from zero to peak amplitude in a duration of $t_i^{SP}$, and another descending from the peak to zero in a time span $t_i^{EP}$. The so-called start-phase time $t_i^{SP}$ and end-phase time $t_i^{EP}$ define an asymmetric slip-rate function which enables modeling of more complexities in source history. With spatial-temporal parameterization of the earthquake source in equation (1), there are five unknowns on each subfault to be determined in the inversion. They are the slip amplitude and rake angle $S_i$ and $\lambda_i$, respectively, the rupture speed $v_i$, and the starting- and ending-phase times $t_i^{SP}$ and $t_i^{EP}$, respectively. Thus the total number of unknown model parameters in each slip-distribution inversion is $5 \times M$.

To enhance the computational efficiency during source inversions, the Green’s functions in equation (1) are calculated beforehand for a given Earth model. For inversions using teleseismic records, it is sufficient to use a global average one-dimensional (1D) model with corrections for crustal structure. However, when using regional and shorter-period records it may be necessary to calculate the Green’s functions in three-dimensional models (Zhao et al., 2006; Hsieh et al., 2016).

2. Method and Seismic Data for Slip-distribution Inversion

The faulting behavior of an earthquake is often described by its so-called focal mechanism, usually represented by a moment tensor acting at a point known as the source centroid location. However, for earthquakes of moderate and large magnitudes it becomes necessary to take the finiteness of the sources into account in order to adequately model the effect of rupture processes on the strong ground motions. Various inversion techniques have been developed over the years for resolving the detailed spatial-temporal rupture processes or slip distributions of earthquakes using teleseismic records (e.g. Olson and Apsel, 1982; Kikuchi and Kanamori, 1982; Hartzell and Heaton, 1983; Ji et al., 2002; Liu and Archuleta, 2004; Piatanesi et al., 2007; Minson et al., 2013; Clayton et al., 2017). The source slip-distribution models provide more complete descriptions of the kinematic characteristics of earthquakes for seismotectonic studies as well as seismic hazard assessment and mitigation purposes.

In this study, we employ the finite-fault inversion method of Ji et al. (2002). The fault plane of an earthquake is discretized in space into $M$ subfaults, and the seismic response at a given station location $r$, $u(r; t)$, can be expressed as the superposition of the waves generated by all subfaults, each of which being considered as a point source (e.g., Hartzell and Heaton, 1983; Ji et al., 2002):

Rather than directly fitting the time series of the broadband records, Ji et al. (2002) proposes a wavelet-decomposition approach in order to better capture the spectral-temporal character-

Figure 2. Distribution of teleseismic stations (inverted green triangles) used in slip-distribution inversion of the 13 November 2016 Kaikoura mainshock. Red star indicates the epicenter of the earthquake, while the beachball displays its GCMT solution.
istics in the waveforms, and quantifies the residuals between model-predicted synthetic waveforms and corresponding records using their respective wavelet coefficients. The objective function to be minimized in the inversion is defined by a $L^1 + L^2$-norm for coefficients of relatively long-period wavelets and a cross-correlation for those of high-frequency ones (Ji et al. 2002; Hsieh et al. 2016). This multi-scale analysis of the seismic waveforms in the wavelet domain leads to enhanced spatial-temporal resolution in source slip-distribution inversions (Ji et al. 2002).

For the inversions of the Kaikoura mainshock and moderate aftershocks, we obtained the broadband seismic records from the waveform data server of the Incorporated Research Institutions for Seismology (IRIS, http://www.iris.edu/). Teleseismic records at stations with epicentral distances of 30°–90° are selected because the propagations of direct P and SH waves in this range are less affected by the heterogeneities in the upper mantle and in the lowermost mantle, and records with low signal-to-noise ratios are rejected. For the Kaikoura mainshock, we selected a total of 89 good waveform traces in the slip-distribution inversion, including 41 body-wave and 48 surface-wave records. Owing to the large magnitude of the mainshock, the overall azimuthal distribution of available records (Figure 2) is very good except for insufficient coverage in the east due to the lack of stations in the Pacific Ocean.

For the three moderate aftershocks of magnitudes $M_w \geq 6.0$, one $M_w 6.5$ event (A1, green beachball in Figure 1a) occurred less than 30 minutes after the mainshock and its waveforms are severely contaminated by the mainshock. Another one has a magnitude of $M_w 6.2$ (A2, black beachball in Figure 1a) and proves to be too small to provide enough records for source inversion. In the end, we are able to obtain a reasonable result only for the November 14 aftershock ($M_w 6.5$, A3, blue beachball in Figure 1a) with a total of 27 teleseismic records.

Figure 3. Result of the slip-distribution inversion for the Kaikoura mainshock. (a) Mapview projection of the slip distribution. The rectangle box depicts the projection of the fault plane on the surface, with the boundary in red indicating the surface trace of the northwest-dipping fault plane. The green star shows the epicenter, while color on the fault plane displays the amount of slip. (b) Moment-rate function. (c) Slip distribution on the fault plane. The big black arrow indicates the fault strike direction. Contours are for rupture time in seconds, and the green star shows the hypocenter. Slip directions are shown by the thin black arrows, whereas the amount of slip is displayed by both the background color and the lengths of the arrows.
3. Rupture Process of the Kaikoura Mainshock
The inversion results for the spatial-temporal slip distribution of the Kaikoura mainshock are displayed in Figure 3, with waveform fitting shown in Figure 4. The source is modeled by a single-plane fault parameterized by 39 × 12 subfaults of area 7.96 km × 7.96 km each, and we use the GCMT solution to orient the fault plane with strike and dip angles of 226° and 33°, respectively, and the USGS hypocenter depth of 15.1 km (Table 1). In the wavelet analysis of teleseismic waveforms, we used wavelets with frequency contents lower than 0.125 Hz for body waves and 0.007 Hz for surface waves. The Green’s functions were computed using the global average 1D model IASP91 (Kennett and Engdahl, 1991) with crustal

![Figure 4](image-url)  
Figure 4. Waveform fitting by the slip-distribution model in Figure 3 for the Kaikoura mainshock. Plotted here are displacement seismograms. (a) Body waves. Records are shown in black, whereas vertical- and transverse-component synthetic waveforms are plotted in red and green, respectively. Station names and azimuths in degrees are given at the beginning of each trace. The number at the end of each trace gives the peak amplitude of the record in micrometers. (b) Same as (a) but for surface waves. The peak amplitudes of the records are given in millimeters.

| Event ID | Origin Time | Latitude (°S) | Longitude (°E) | Depth (km) | \( M_w \) | Focal Mechanism (strike/dip/rake) |
|----------|-------------|---------------|----------------|------------|---------|----------------------------------|
| Mainshock | 2016-11-13 11:02:56 | 42.737 | 173.054 | 15.1 | 7.8 | GCMT: 226°/33°/141° |
| A1 | 2016-11-13 11:32:06 | 42.321 | 173.669 | 10.0 | 6.5 | USGS: 218°/16°/109° |
| A2 | 2016-11-13 13:31:25 | 42.309 | 173.696 | 2.1 | 6.2 | USGS: 243°/78°/166° |
| A3 | 2016-11-14 00:34:22 | 42.606 | 173.254 | 9.0 | 6.5 | GCMT: 248°/89°/175° |

Notes: The Event IDs for the aftershocks (A1, A2 and A3) are those used in Figures 1a, 6 and 8 as well as in the main text. Unless noted otherwise, all information in this table comes from the USGS website for Significant Earthquakes Archive (https://earthquake.usgs.gov/earthquakes/browse/significant.php). Depth here refers to the hypocenter depth. Focal mechanisms for the mainshock and aftershock A3 are from the GCMT (http://www.globalcmt.org/CMTsearch.html) catalog. GCMT solutions are not available for aftershocks A1 and A2.

Lo Y-C et al.: Slip distribution of 2016 Kaikoura earthquake
corrections based on CRUST2.0 (Bassin et al., 2000). We adopted a single-plane fault model in the source inversion using teleseismic waveforms. Field reconnaissance of surface ruptures conducted by the GNS Science Team following the Kaikoura earthquake as well as geodetic and InSAR observations of ground deformation indicate that the Kaikoura mainshock involved ruptures on multiple faults (e.g. Bradley et al., 2017; Hamling et al., 2017). Here, we used teleseismic waveforms only in our inversion, and the result showed that, apart from the waveforms of a few body waves and amplitudes of several surface waves, a single-plane fault model yields excellent fit to most of the body and surface waveforms (Figure 4), leading to a first-order image of the earthquake’s source slip distribution.

To further validate our slip-distribution model, we conducted a bootstrap test in which random selections of 80% of the available waveform traces were used to invert for the slip distribution. The bootstrap test shown in Figure 5 demonstrates the adequacy of the available waveforms and the robustness and stability of the rupture inversion result.

The inversion results shown in Figure 3 indicate that the Kaikoura mainshock occurred on the northwest-dipping fault plane. The teleseismic slip pattern reveals a relatively smooth unilateral rupture propagation from the hypocenter in the northeast direction, with the main slip zone extending between 50 km and 180 km northeast of the hypocenter. The region around the hypocenter is almost devoid of slip, a not uncommon phenomenon also seen in the source slip models of other large as well as moderate earthquakes (e.g. Avouac et al., 2015; Grandin et al., 2015; Hsieh et al., 2016). The maximum slip of ~4 m occurred ~100 km northeast and down-dip of the hypocenter at a depth of ~25 km and at ~70

![Figure 5](image_url)
s after the origin time. The rupture propagates northeastward for almost 200 km from the hypocenter. Even though the rupture lasts for about 100 s, most of the energy was released in the short time window ~60–80 s after the origin time.

4. Discussion

The slip-distribution pattern of the Kaikoura mainshock exhibits a mixture of thrust and right-lateral strike-slip motions. The earthquake was initiated by a weak rupture near the hypocenter. Many studies have suggested that the initial rupture occurred on shallow crustal faults near the epicenter (e.g., Zhang et al., 2017; Cesca et al., 2017; Duputel and Revera, 2017; Hamling et al., 2017; Hollingsworth et al., 2017; Shi et al., 2017; Wang et al., 2018). However, as shown in Figure 3c, there seems to be slip, albeit small, at a depth of 15 km and greater at ~10 s before the shallow-rupture later. The moderate hypocenter depth of 15 km is further evidence in favor of a deeper rupture initiation. Therefore, we argue for the alternative scenario that the Kaikoura mainshock started from a rupture on the megathrust. High-resolution imaging of the fault system in the vicinity of the hypocenter is necessary if the role of the megathrust in the initiation of the Kaikoura earthquake is to be clarified. There are three distinct pockets of slip zones with different senses of motion (Figure 3c): In the early stage of 20–35 s, the slip is dominated by thrust motion in a depth range of 10 km and shallower, with a vertical offset of as much as 1.5 m on the ocean floor nearly 60 km northeast of the epicenter. Starting from ~50 s, a bi-modal pattern develops: an oblique thrust motion concentrating in a greater depth (20–30 km) and extending ~80–120 km northeast of the hypocenter; another almost purely strike-slip motion occurring at a shallower depth (15 km to surface). This latter strike-slip motion lasts for about 30 s.

Figure 6. Result of the slip-distribution inversion for the $M_w$ 6.5 aftershock A3 on 14 November 2016 (blue beachball in Figures 1a and 8). (a) Distribution of teleseismic stations (inverted triangles) used in slip-distribution inversion. Red star indicates the location of the earthquake, while the beachball displays the GCMT solution. (b) Mapview projection of the slip distribution. The green star shows the epicenter. Color on the fault plane shows the amount of slip. (c) Moment-rate function. (d) Slip distribution on the fault plane. Contours are for rupture time in seconds, and the green star shows the hypocenter. Slip directions are depicted by the black arrows, whereas the amount of slip is displayed by both the background color and the lengths of the arrows.
and extends horizontally in a distance range of 90–180 km north-east of the hypocenter. The horizontal offset on the ocean floor is ~2 m.

The moment-rate function in Figure 3b displays a similar process seen in the spatial pattern. The earthquake was initiated by the mostly thrust motion, presumably caused by subduction at the Hikurangi Trench. This relatively weak thrust at shallow depth appears to have run into resistance at ~35 s and, after a brief slowdown, triggered the ruptures at ~60 s in the two major slip zones: a deeper one with oblique thrust motion in the subduction zone and another with strike-slip motion near the surface.

Figure 6 shows the slip pattern of the November 14 Mw 6.5 aftershock (A3 in Figure 1a and Table 1), which exhibits a bi-lateral rupture. In contrast to the mainshock, this aftershock occurred on a fault plane at a shallower depth with a much steeper angle (89°). Once again there is very little slip in the vicinity of the hypocenter, and the two main slip zones with almost purely strike-slip motion are concentrated some 20–40 km away from the hypocenter. The stronger slip zone is located mostly above 10-km depth and ~30 km northeast of the hypocenter. These two slip zones could be ruptures on two different crustal faults: the Humps southwest of the hypocenter and the Hundalee in the northeast (see Figure 1a for the fault locations).

The pattern of slip distribution from our teleseismic waveform inversion here as well as surface rupture observations reported elsewhere suggest that the Kaikoura earthquake occurred most likely due to the activation of two northeast-southwest trending fault systems at different depths and with different dipping angles and faulting mechanisms: a deeper low-angle northwest-dipping oblique-thrust fault and a number of shallower and nearly vertical right-lateral strike-slip faults (Figure 1c). In this scenario, our slip-distribution model on a single fault represents the superposed effect of the slip motions on these two fault systems, as shown in Figure 7 where we decompose the slip vectors on the fault plane of the Kaikoura mainshock into thrust (vertical) and strike-slip (horizontal) components.

The decomposition of slip on the fault plane in Figure 7 clearly shows that the Kaikoura mainshock is dominated by horizontal slip motion, which is directly controlled by the convergence between the Pacific and Australian plates (Figure 1b). The oblique

Figure 7. Decomposition of (a) the source slip vectors of the November 13, 2016 Kaikoura mainshock (same as Figure 3c) into (b) thrust (vertical) and (c) strike-slip (horizontal) components.
thrust in the deeper slip zone (20–30 km depth and 75–100 km northeast of the hypocenter) with similar horizontal and vertical components appears roughly in line with this inter-plate motion. To the southwest and closer to the epicenter, the slip zone gets shallower with a reduced horizontal component, likely a combined effect of the gradual termination of subduction at depth and the transfer of horizontal motion on to the Marlborough Fault System. Thus, the initial thrust of the Kaikoura mainshock implies that the westward subduction of the Pacific Plate extends under the on land region in the northeast corner of the South Island. Further northeast, the deeper oblique thrust motion is effectively partitioned at shallower depth into purely right-lateral strike-slips on the major northeast-southwest trending faults and diffused uplifts by numerous small faults (Nicol and van Dissen, 2002), resulting in the dominance of strike-slip motion during major earthquakes such as the Kaikoura mainshock. The strike-slip motions at shallower depths during the mainshock as well as on the multiple high-angle seismogenic faults of the moderate aftershocks, which are subsidiary strike-slip faults on the hanging wall of the subduction zone or megathrust (Figure 1c), were perhaps triggered by dynamic rupturing during the mainshock on the megathrust along the Hikurangi Trench.

In order to further examine the seismotectonic characteristics of the Kaikoura earthquake sequence, we plot in Figure 8 the slip distributions of the mainshock and aftershock A3 together with the distribution of two-week aftershocks of $M \geq 3.5$ (GeoNet, http://info.geonet.org.nz). An interesting observation is that the stronger slip zone of the aftershock A3 northeast of its hypocenter (blue region on the fault plane for A3) appears to be situated right on top of the initial thrust slip zone of the mainshock. Although the two-week aftershocks are seemingly distributed randomly, they tend to cluster around the edges of the major slip zones of the mainshock. In particular, the three moderate aftershocks (A1, A2 and A3) are all located near the borders of the main.

**Figure 8.** Surface projections of the slip distributions of the November 13, 2016 Kaikoura mainshock ($M_w 7.8$) and the November 14 moderate aftershock ($M_w 6.5$) plotted together with the aftershocks of $M \geq 3.5$ occurred within two weeks following the mainshock. The rectangle boxes are surface projections of the fault planes with the sides in red indicating the faults’ surface traces. The red star and beachball depict the location and GCMT mechanism of the mainshock with slip amplitude shown by yellow to red colors. Location and GCMT mechanism of the November 14 aftershock A3 are indicated by the blue star and beachball, with slip amplitude shown by light to dark blue colors. Also plotted are the locations (stars) and GCMT mechanisms (beachballs) of the other two moderate aftershocks A1 and A2. Circles are epicenters of aftershocks, with colors and sizes represent the source depths and magnitudes, respectively, as indicated in the legend.
slip zones of the mainshock. This phenomenon has also been observed in other large earthquakes (e.g. Yue et al., 2016). As slip-distribution results become more routinely available lately, it can be expected that results for future earthquakes will yield more evidence regarding the relationship between the slip zones of the mainshock and the locations of strong aftershocks, which, combined with existing knowledge of local active faults, may provide practical information on seismic hazard assessments after the occurrence of large earthquakes.

In the slip distribution for the Kaikoura mainshock in Figure 8 obtained using a single-plane fault, we can also see some interesting linkage between the slip motions at depth and the surface ruptures observed from post-earthquake field surveys. For instance, the coastal uplift of ~1 m near Kaikoura Peninsula (Figure 1a), some 70 km northeast of the mainshock hypocenter, is roughly on top of the shallow thrust slip zone where there is nearly 2 m of vertical slip in the depth range of 5–10 km (Figures 3 and 8). About 30 km further northeast, where 2–3 m of coastal uplift was reported near the Papatea Fault (Figure 1), is where the most intense rupture zone is located, with an oblique thrust motion (up to ~2 m of vertical slip) at a depth range of 20–30 km. The change in the slip pattern (Figure 3) from thrust to oblique thrust and finally to strike-slip is also in very good agreement with the northeastward increase in horizontal surface offsets found in geodetic observations (Hamling et al., 2017).

5. Conclusions

A source slip-distribution model obtained from teleseismic waveform inversion suggests that the November 2016 Kaikoura earthquake was initiated by minor thrust motion due to the subduction of the Pacific Plate under the Australian Plate. The initial rupture grew into rupture at shallower depth, and then developed into two larger failures northeast of the initial thrust, one on the down-dip section of the subduction interface with oblique thrust and another at shallow depth with purely right-lateral strike-slip motion. Given that our inversion is based on a single-fault source model, the latter appears to have resulted from the multiple high-angle strike-slip faults within the Marlborough Fault System, which led to the highly complex surface ruptures reported by geodetic observations and post-earthquake field reconnaissance. The slip pattern implies that the westward subduction of the Pacific Plate along the Hikurangi Trench extends under the on land region near Kaikoura Peninsula in the northeast corner of the South Island. The dominance by the near-surface strike-slip motion indicates an effective partitioning of the oblique motion of the plate subduction into horizontal slips on major strike-slip faults in the Marlborough Fault System capable of generating large earthquakes, and diffused uplifts through numerous small faults. Slip distribution of the Kaikoura mainshock also shows that aftershocks tend to cluster around the edges of major slip zones of the mainshock, which may provide practical information on seismic hazard assessments after the occurrence of large earthquakes in the future.

Acknowledgments

Teleseismic waveform records used in this study are obtained from the Incorporated Research Institutions for Seismology (IRIS, http://www.iris.edu/). Information on the mainshock and the three moderate aftershocks A1, A2 and A3 comes from the USGS website for Significant Earthquakes Archive (https://earthquake.usgs.gov/earthquakes/browse/significant.php). Centroid moment tensors of earthquakes are available from the Global Centroid Moment Tensor Project (GCMT, http://www.globalcmt.org/). Aftershock locations are provided by the GeoNet Earthquake Catalog (http://info.geonet.org.nz/display/appdata/Earthquake+Catalogue). The Generic Mapping Tools of Wessel and Smith (1998) was used to prepare some of the figures.

References

Anderson, H., and Webb, T. H. (1994). New Zealand seismicity: patterns revealed by the upgraded National Seismograph Network. New Zealand J. Geol. Geophys., 37, 477–493. https://doi.org/10.1080/00288306.1994.9514633
Avouac, J.-P., Meng, L. S., Wei, S. J., Wang, T., and Ampuero, J.-P. (2015). Lower edge of locked Main Himalaya Thrust unzipped by the 2015 Gorkha earthquake. Nat. Geosci., 8, 708–711. https://doi.org/10.1038/ngeo2518
Barnes, P. M. (2009). Postglacial (after 20 ka) dextral slip rate of the offshore Alpine fault, New Zealand. Geology, 37, 3–6. https://doi.org/10.1111/j.1096-9864.1
Bassin, C., Laske, G., and Masters, T. G. (2000). The current limits of resolution for surface wave tomography in North America. EOS Trans. AGU, 81, F897.
Bradley, B. A., Razafindrakoto, N. T., and Polak, V. (2017). Ground-motion observations from the 14 November 2016 Mw 7.8 Kaikoura, New Zealand, earthquake and insights from broadband simulations. Seismol. Res. Lett., 88, 740–756. https://doi.org/10.1785/0201601622
Cesca, S., Zhang, Y., Mouslopoulou, V., Wang, R., Saul, J., Savage, M., Helmann, S., Kufner, S.-K., Oncken, O., and Dahm, T. (2017). Complex rupture process of the Mw7.8, 2016, Kaikoura earthquake, New Zealand, and its aftershock sequence. Earth Planet. Sci. Lett., 478, 110–120. https://doi.org/10.1016/j.epsl.2017.08.024
Clayton, B. S., Hartzell, S. H., Moschetti, M. P., and Minson, S. E. (2017). Finite-fault Bayesian inversion of teleseismic body waves. Bull. Seismol. Soc. Am., 107, 1526–1544. https://doi.org/10.1785/0120160268
COMET-NERC. http://comet.nerc.ac.uk
Duputel, Z., and Rivera, L. (2017). Long-period analysis of the 2016 Kaiköura earthquake. Phys. Earth Planet. Inter., 265, 62–66. https://doi.org/10.1016/j.pepi.2017.02.004
GCMT. http://www.globalcmt.org/CMTsearch.html
GeoNet. http://info.geonet.org.nz
GeoNet Earthquake Catalogue. http://info.geonet.org.nz/display/appdata/Earthquake+Catalogue
Gledhill, K., Ristau, J., Reyners, M., Fry, B., and Holden, C. (2011). The Darfield (Canterbury, New Zealand) Mw 7.1 earthquake of September 2010: A preliminary seismological report. Seismol. Res. Lett., 82, 378–386. https://doi.org/10.1785/02sr110378
Grandin, R., Vallée, M., Satriano, C., Lacassin, R., Klinger, Y., Simoes, M., and Bollinger, L. (2015). Rupture process of the Mw 7.9 2015 Gorkha earthquake (Nepal): Insights into Himalayan megathrust segmentation. Geophys. Res. Lett., 42, 8373–8382. https://doi.org/10.1002/2015GL066044
GSI. http://www.gsi.go.jp/cais/topic161117-index-e.html
Hamling, I. J., Heinsdottir, S., Clark, K., Elliott, J., Liang, C. R., Fielding, E., Litchfield, N., Villamor, P., Wallace, L., … Stirling, M. (2017). Complex multifaith rupture during the 2016 Mw 7.8 Kaikoura earthquake, New Zealand. Science, 356, eaam7194. https://doi.org/10.1126/science.aam7194
Hartzell, S. H., and Heaton, T. H. (1983). Inversion of strong ground motion and teleseismic waveform data for the fault rupture history of the 1979 Imperial Valley, California, earthquake. Bull. Seismol. Soc. Am., 73, 1553–1583.
Hollingsworth, J., Ye, L. L., and Avouac, J.-P. (2017). Dynamically triggered slip on a splay fault in the Mw 7.8, 2016 Kaikoura (New Zealand) earthquake. Geophys. Res. Lett., 44, 3517–3525. https://doi.org/10.1002/2016GL072228
Hsieh, M.-C., Zhao, L., Ji, C., and Ma, K.-F. (2016). Efficient inversions for earthquake slip distributions in 3D structures. Seismol. Res. Lett., 87, 1342–1354. https://doi.org/10.1785/0220160050

IRIS. http://www.iris.edu

Ji, C., Helmberger, D. V., Wald, D. J., and Ma, K.-F. (2003). Slip history and dynamic implications of the 1999 Chi-Chi, Taiwan, earthquake. J. Geophys. Res., 108(B9), 2412. https://doi.org/10.1029/2002JB001764

Ji, C., Wald, D. J., and Helmberger, D. V. (2002). Source description of the 1999 Hector Mine, California earthquake, Part I: Wavelet domain inversion theory and resolution analysis. Bull. Seismol. Soc. Am., 92, 1192–1207. https://doi.org/10.1785/012000916

Kennett, B. L. N., and Engdahl, E. R. (1991). Traveltimes for global earthquake location and phase identification. Geophys. J. Int., 105, 429–465. https://doi.org/10.1111/j.1365-246X.1991.tb06724.x

Kikuchi, M., H. and Kanamori, H. (1982). Inversion of complex body waves. Bull. Seismol. Soc. Am., 72, 491–506.

Langridge, R. M., Campbell, J., Hill, N. L., Pere, V., Pope, J., Pettinga, J., Estrada, B., and Berryman, K. R. (2003). Paleoseisimology and slip rate of the Conway Segment of the Hope Fault at Greenburn Stream, South Island, New Zealand. Ann. Geophys., 46, 1119–1139. https://doi.org/10.4401/ag-3449

Langridge, R. M., Villamor, R., Basili, R., Almond, P., Martinez-Diaz, J. J. and Canora, C. (2010). Revised slip rates for the Alpine fault at Inchbonnie: Implications for plate boundary kinematics of South Island, New Zealand. Lithosphere, 2, 139–152. https://doi.org/10.1130/L88.1

Litchfield, N. J., van Dissen, R., Sutherland, R., Barnes, P. M., Cox, S. C., Norris, R., Beavan, R. J., Langridge, R., Villamor, P., … Clark, K. (2014). A model of active faulting in New Zealand. New Zealand J. Geol. Geophys., 57, 32–56. https://doi.org/10.1080/00288306.2013.854256

Little, T. A., and Jones, A. (1998). Seven million years of strike-slip and related off-fault deformation, northeastern Marlborough fault system, South Island, New Zealand. Tectonics, 17, 285–302. https://doi.org/10.1029/97TC03148

Liu, P. C., and Archuleta, R. J. (2004). A new nonlinear finite fault inversion with three-dimensional Green’s functions: Application to the 1989 Loma Prieta, California, earthquake. J. Geophys. Res., 109, B02318. https://doi.org/10.1029/2003JB002625

Minson, S. E., Simons, M., and Beck, J. L. (2013). Bayesian inversion for finite fault earthquake source models I-theory and algorithm. Geophys. J. Int., 194, 1701–1726. https://doi.org/10.1093/gji/ggt180

Nicolas, A., and van Dinno, R. (2002). Up-dip partitioning of displacement components on the oblique-dip Clarence Fault, New Zealand. J. Structural Geol., 24(1521), 1535. https://doi.org/10.1016/S0191-8141(01)00141-9

NIWA. https://niwa.co.nz/news/scientists-detect-hugefault-rupture-offshore-from-kaikoura

Olson, A. H., and Apsel, R. J. (1982). Finite faults and inverse theory with applications to the 1979 Imperial Valley earthquake. Bull. Seismol. Soc. Am., 72, 1969–2001.

Piatanesi, A., Cirrella, A., Spudich, P., and Cocco, M. (2007). A global search inversion for earthquake kinematic rupture history: Application to the 2000 western Tottori, Japan earthquake. J. Geophys. Res., 112, B07314. https://doi.org/10.1029/2006JB004821

Power, W., Clark, K., King, D. N., Borreiro, J., Howarth, J., Lane, E. M., Goring, D., Goff, J., Chagué-Goff, C., … Benson, A. (2017). Tsunami runup and tide-gauge observations from the 14 November 2016 M7.8 Kaikoura earthquake, New Zealand. Pure Appl. Geophys., 174, 2457–2473. https://doi.org/10.1007/s00024-017-1566-2

Shi, X.-H., Wang, Y., Liu-Zeng, J., Weldon, R., Wei, S. J., Wang, T., and Sieh, K. (2017). How complex is the 2016 Mw 7.8 Kaikoura earthquake, South Island, New Zealand?. Sci. Bull., 62, 309–311. https://doi.org/10.1016/j.scbull.2017.01.033

USGS. https://earthquake.usgs.gov/earthquakes/eventpage/us1000778i#executive

USGS Significant Earthquakes Archive. https://earthquake.usgs.gov/earthquakes/browse/significant.php

Wang, T., Wei, S. J., Shi, X. H., Qiu, Q., Li, L. L., Peng, D. J., Weldon, R. J., and Barbot, S. (2018). The 2016 Kaikoura earthquake: Simultaneous rupture of the subduction interface and overlying faults. Earth Planet. Sci. Lett., 482, 44–51. https://doi.org/10.1016/j.epsl.2017.10.056

Wessel, P., and Smith, W. (1998). New, improved version of the Generic Mapping Tools released. Eos. Trans. AGU, 79, 579. https://doi.org/10.1029/98EO00426

Wikipedia. http://en.wikipedia.org/wiki/2016_Kaikoura_earthquake.

Yue, H., Simons, M., Duputel, Z., Jiang, J. L., Fielding, E., Liang, C., Owen, S., Moore, A., Riel, B., … Samsonov, S. V. (2016). Depth varying rupture properties during the 2015 Mw7.8 Gorkha (Nepal) earthquake. Tectonophysics, 714–715, 44–54. https://doi.org/10.1016/j.tecto.2016.07.005

Zhang, H., Koper, K. D., Pankow, K., and Ge, Z. X. (2017). Imaging the 2016 Mw 7.8 Kaikoura, New Zealand, earthquake with teleseismic P waves: A cascading rupture across multiple faults. Geophys. Res. Lett., 44, 4790–4798. https://doi.org/10.1002/2017GL073461

Zhao, L., Chen, P., and Jordan, T. H. (2006). Strain Green's tensors, reciprocity, and their applications to seismic source and structure studies. Bull. Seismol. Soc. Am., 96, 1753–1763. https://doi.org/10.1785/0120050253