Complex multifault rupture during the 2016 $M_w$ 7.8 Kaikōura earthquake, New Zealand

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INTRODUCTION: On 14 November 2016 (local time), northeastern South Island of New Zealand was struck by a major moment magnitude ($M_w$) 7.8 earthquake. The Kaikōura earthquake was the most powerful experienced in the region in more than 150 years. The whole of New Zealand reported shaking, with widespread damage across much of northern South Island and in the capital city, Wellington. The earthquake straddled two distinct seismotectonic domains, breaking multiple faults in the contractional North Canterbury fault zone and the dominantly strike-slip Marlborough fault system.

RATIONALE: Earthquakes are conceptually thought to occur along a single fault. Although this is often the case, the need to account for multiple segment ruptures challenges seismic hazard assessments and potential maximum earthquake magnitudes. Field observations from many past earthquakes and numerical models suggest that a rupture will halt if it has to step over a distance as small as 5 km to continue on a different fault. The Kaikōura earthquake’s complexity defies many conventional assumptions about the degree to which earthquake ruptures are controlled by fault segmentation and provides additional motivation to rethink these issues in seismic hazard models.

RESULTS: Field observations, in conjunction with interferometric synthetic aperture radar (InSAR), Global Positioning System (GPS), and seismology data, reveal the Kaikōura earthquake to be one of the most complex earthquakes ever recorded with modern instrumental techniques. The rupture propagated northward for more than 170 km along both mapped and unmapped faults before continuing offshore at the island’s northeastern extent. A tsunami of up to 3 m in height was detected at Kaikōura and at three other tide gauges along the east coast of both the North and South Islands. Geodetic and geological field observations reveal surface ruptures along at least 12 major crustal faults and extensive uplift along much of the coastline. Surface displacements measured by GPS and satellite radar data show horizontal offsets of ~6 m. In addition, a fault-bounded block (the Papatea block) was uplifted by up to 8 m and translated south by 4 to 5 m. Modeling suggests that some of the faults slipped by more than 20 m, at depths of 10 to 15 km, with surface slip of ~10 m consistent with field observations of offset roads and fences. Although we can explain most of the deformation by crustal faulting alone, global moment tensors show a larger thrust component, indicating that the earthquake also involved some slip along the southern end of the Hikurangi subduction interface, which lies ~20 km beneath Kaikōura. Including this as a fault source in the inversion suggests that up to 4 m of predominantly reverse slip may have occurred on the subduction zone beneath the crustal faults, contributing ~10 to 30% of the total moment.

CONCLUSION: Although the unusual multifault rupture observed in the Kaikōura earthquake may be partly related to the geometrically complex nature of the faults in this region, this event emphasizes the importance of reevaluating how rupture scenarios are defined for seismic hazard models in plate boundary zones worldwide.

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On 14 November 2016, northeastern South Island of New Zealand was struck by a major moment magnitude ($M_w$) 7.8 earthquake. Field observations, in conjunction with interferometric synthetic aperture radar, Global Positioning System, and seismology data, reveal this to be one of the most complex earthquakes ever recorded. The rupture propagated northward for more than 170 kilometers along both mapped and unmapped faults before continuing offshore at the island’s northeastern extent. Geodetic and field observations reveal surface ruptures along at least 12 major faults, including possible slip along the southern Hikurangi subduction interface: extensive uplift along much of the coastline; and widespread anelastic deformation, including the ~8-meter uplift of a fault-bounded block. This complex earthquake defies many conventional assumptions about the degree to which earthquake ruptures are controlled by fault segmentation and should motivate reevaluation of these issues in seismic hazard models.

Whether multiple fault segments can rupture during a single earthquake is critical for our understanding of seismic hazard and potential maximum earthquake magnitudes. Variations in stress levels along a rupture and geometric complexities, such as fault stepovers, are thought to be a primary control of final rupture length (1, 2). Whereas numerical models and field observations suggest that fault stepovers of more than 4 to 5 km can halt a rupture’s propagation (1, 3, 4), near-instantaneous triggering over distances of more than 50 km has been documented (5, 6). Furthermore, recent observations indicate that fault networks with both optimally oriented and misoriented faults can rupture during a single earthquake (7, 8). Insights from complex ruptures involving multiple faults—including the 2010–2011 Christchurch earthquake sequence in New Zealand (9) and El Mayor–Cucapah in Mexico (7, 8)—are starting to feed into seismic hazard models, thus relaxing some of the assumptions surrounding fault segmentation and multifault ruptures (20).

Here we show detailed geodetic and geological evidence of highly complex fault rupture during the 14 November 2016 (13 November 11:02 UTC) moment magnitude ($M_w$) 7.8 Kaikōura earthquake in northeastern South Island of New Zealand. The earthquake resulted in surface slip of more than 10 m along multiple faults, several of which were previously unmapped or considered inactive (Fig. 1), despite New Zealand having one of the most accurate and comprehensive maps of active faults worldwide (11). The earthquake ruptured faults across two distinct seismotectonic domains with fundamentally different characteristics (22), a scenario that would have been excluded from seismic hazard models.

Oblique convergence between the Pacific and Australian plates at rates of 39 to 48 mm/year (13) dominates New Zealand’s tectonics. In the North Island, relative plate motion is mostly accommodated by subduction along the Hikurangi subduction zone (14, 15), whereas central South Island tectonics is dominated by dextral transpression on the Alpine fault (13). The strike-slip-dominated Marlborough fault system (MFS) (Fig. 1) in northern South Island occupies the transition from the Hikurangi subduction zone to the strike-slip-dominated Alpine fault (16, 17). South of the MFS, in the North Canterbury region, active deformation is dominated by transpression, which is distributed among a number of slowly deforming faults and folds, including the Humps and Hundalee faults (18). Although the southern end of the subducting Pacific slab underlies the MFS at depths of 25 to 30 km (19), Quaternary and geodetic strain (16, 17, 20) indicate that the majority (>75%) of the relative plate motion within northern South Island is accommodated at the surface by faults in the MFS. Slip rates through the MFS decrease from south to north. The northernmost faults (Awatere, Clarence, and Wairau) have slip rates in the range of 4 to 8 mm/year (21–23). In contrast, some of New Zealand’s fastest-slipping onshore faults can be found at the southeastern edge of the MFS: The Hope and Kekerengu faults have Quaternary slip rates varying from 18 to 25 mm/year (20, 24–26). As the Hope fault approaches the coastline, it transfers much of its slip to the Jordan thrust, which has a more northerly strike (and hence a larger reverse component). Further north, the Jordan thrust slip is transferred to the mostly dextral strike-slip Kekerengu fault in northeastern South Island (12) (Fig. 1).

The 14 November 2016 Kaikōura earthquake

The $M_w$ 7.8 Kaikōura earthquake struck just after midnight on 14 November, with an epicenter ~20 km south of the Hope fault (Fig. 1). The earthquake was the most powerful seismic event in that area in more than 150 years. Shaking was widely felt throughout New Zealand, with extensive damage occurring across northern South Island. Global moment tensor solutions showed a combination of reverse and strike-slip faulting, with a strong non–double-couple component. Aftershocks follow a broad northeast-to-southwest trend proximal to the Humps and Hundalee faults for ~80 km extending offshore near Kaikōura (Fig. 1 and fig. S1). The aftershocks then step north, approximately following the Jordan thrust and Kekerengu faults, with a large cluster of events occurring in the Cape Campbell and Lake Grassmere area (Fig. 1), the site of a $M_w$ 6.8 earthquake in 2013 (27). Regional moment tensors (28) for aftershocks show a mixture of reverse and strike-slip mechanisms, with the majority of events occurring in the upper 20 km (fig. S1). The earthquake generated a tsunami (up to 3 m at Kaikōura), which was detected at four tide gauges along the east coast of both the North and South Islands. We used margigrams from these tide-gauge stations to determine the travel times of the first arrivals of the tsunami wave field located at Kaikōura (0.11 hours), Castlepoint (0.83 hours), Wellington (0.95 hours), and Christchurch (1.53 hours). Simple travel time inversion, assuming reciprocity between the source of the tsunami and the location of the tide gauges, places the source of the tsunami in the coastal area ranging from just south of Kaikōura northward to Cape Campbell (Fig. 1 and fig. S2).
which corresponds to the general area of coastal uplift.

Field observations after the earthquake recorded major (meter-scale) ground surface ruptures on some or all of at least three transpressional faults (Fig. 1). In the North Canterbury region, near the epicenter, two previously identified east-northeast–to northeast-striking faults displayed oblique meter-scale, up-to-the-northwest surface rupture of as much as 2 m, with similar dextral strike-slip (the Humps fault zone) and subordinate strike-slip (Hundalee fault). In addition, oblique dip-slip sinistral strike-slip surface rupture of typically ~1 m was observed on at least two previously unidentified north- to north-northwest–striking faults. The Hundalee fault rupture extended across the coast and offshore, with its northwest-dipping side marking the southern limit of recognizable coseismic coastal uplift (see below). Within the MFS, meter-scale dextral strike-slip surface rupture occurred on at least five northeast-striking structures: the Upper Kowhai fault, Jordan thrust, Fidget fault, Kekerengu fault, and the offshore Needles fault. The largest displacements documented so far on the onshore northeast-striking faults are 12 m dextral offset on the Kekerengu fault, with ~1 to 3 m of vertical offset, and as much as 4 m dextral offset on the Jordan thrust. Perhaps the biggest surprise was the large amount of surface displacement on the north-northwest–striking oblique reverse-sinistral Papatea fault, with as much as 5 to 6 m of strike-slip and 6 to 7 m of dip-slip. Minor (<0.5 m) surface displacements were observed on two faults near Cape Campbell, as well as on the Hope fault, where it meets the coast.

Uplift observed along the Kaikoura coast was highly variable, with field measurements ranging from 0.6 to 4.8 m (Fig. 2). No coastal change was observed south of the Hundalee fault, but on the northern side of the fault, there was coastal uplift of 1.6 ± 0.3 m. The amount of uplift decreased northward toward Kaikoura Peninsula, which was uplifted ~0.9 m. Coastal uplift remained low for ~12 km north of Kaikoura Peninsula before increasing to ~2 m of uplift south of the Hope fault. Between the Hope fault and the Papatea fault, coastal uplift was relatively high at ~2 to 3 m. Maximum coastal uplift of 4.8 ± 0.5 m occurs on the 700-m-wide block between the two strands of the Papatea fault. There appeared to be little or no uplift between the Kekerengu and Papatea faults. Consistent uplift of 2.5 to 3 m was measured inboard of the mapped segments of the onshore Kekerengu fault and the submarine Needles fault, confirming continuous submarine fault rupture between these two faults.

Continuous and campaign Global Positioning System (GPS) data (29) recorded displacements with more than 6 m of lateral motion in the vicinity of Cape Campbell (Figs. 1 and 2) and uplift of up to 2 m at the northern end of the Seaward Kaikoura mountain range (Fig. 2). Widespread uplift was also observed in the vicinity of Kaikoura, with areas of subsidence found inland of the Clarence fault and to the south of the Humps and Hundalee faults in North Canterbury (Figs. 1 and 2). Two sites, located to the south of the Kekerengu fault, show westward motion of ~2 m, consistent with the right-lateral offsets. In addition to GPS data, synthetic aperture radar (SAR) data were acquired by the Sentinel and ALOS-2 missions of the European and Japanese space agencies, respectively (tables S1 and S3). Both ascending (Sentinel-1A and ALOS-2) and descending (ALOS-2) interferograms corroborated many of the early field observations but also revealed a much more complex fault rupture than was initially realized. Both the ascending and descending interferograms retain good coherence across most of the region, with maximum line-of-sight (LOS) changes of ~1.3 m in the ascending and ~3 m in the descending tracks (Fig. 3 and fig. S4). Some loss of coherence has been observed along the coast and near many of the ground ruptures; this is a result of large phase gradients in the nearfield, extensive landslide activity, and changes to the ground surface.

The Sentinel-1 and ALOS-2 images reveal the largest displacements in two distinct regions. In
the south, deformation is concentrated along a northeast-southwest trend running along the Humps fault zone and toward the Hundalee fault (Fig. 3 and fig. S4). The deformation then steps north where it broadens inland from Kaikōura, consistent with slip along the Upper Kowhai fault, Jordan thrust, and onto the Kekerengu fault, as observed in the field (Fig. 3). In addition to the interferometric SAR (InSAR) data, multi-aperture InSAR (MAI) and range and azimuth offsets, which do not suffer from decorrelation in the nearfield, show a number of sharp discontinuities corresponding with ground observations (fig. S4). Using the range and azimuth offsets from the ascending and an additional descending Sentinel pair (note that the phase data are not used due to the long temporal baseline), we also generated a full three-dimensional (3D) displacement field (Fig. 4) (29). The radar-derived displacement field shows good agreement with the GPS and geological field observations (Fig. 4). Across the Kekerengu fault, there are horizontal displacements of ~10 m with hanging wall uplift. Some of the largest deformation is observed in a 50-km² region south of the convergence point between the Jordan thrust and the Kekerengu and Papatea faults; this area has been uplifted by as much as 8 m and translated south by 4 to 5 m (Fig. 4). Both the satellite-derived deformation and field observations show a seaward decrease in the amount of uplift and left-lateral offsets along the Papatea fault. In the vicinity of the epicenter, there are two discrete regions of uplift between the Humps fault zone and the Hope fault. This is also observed in the MAI offsets (fig. S4), which show north-northeast–south-southwest discontinuities associated with slip at depth. Scattered north-south-trending sinistral-reverse surface ruptures, mapped in the field in association with both faults, could be accommodating some of the uplift, but their displacements do not account for the uplift detected by InSAR.

Deformation modeling

To develop a slip model for the earthquake, we used the ascending and descending phase data, coseismic offsets from 226 continuous and campaign GPS sites from the South and North Islands. Although a number of additional scenes have been acquired by the Sentinel and ALOS-2 satellites since the earthquake, to minimize the effects of postseismic deformation and aftershocks we used only the earliest coseismic pairs, which were both acquired on 15 November, ~24 to 36 hours after the mainshock. We fixed the dip of each fault to its geologically estimated value (22) and discretized each fault into ~2-by-~3-km patches along strike...
and downdip, respectively, assuming a constant dip \((29)\). The fault geometry is constrained on the basis of discontinuities observed in the InSAR data, including azimuth and range offsets, and field observations of coastal uplift (Fig. 3 and fig. S4). The earthquake is modeled as a set of rectangular dislocations in an elastic half-space \((30)\). The deformation pattern observed around the Papatea fault could not be fit using an elastic model (such as ours), and we expect that most of the deformation associated with the Papatea block is related to anelastic deformation within a fault-restraining bend (see Discussion and conclusions section). For this reason, we do not include the Papatea fault in our slip inversions, and data around the uplifted block was removed. We fixed the depth to the base of each fault to 25 km and solved for the slip and rake direction of each fault patch using a nonnegative least-squares inversion \((29, 31)\).

The best-fit crustal fault model, which explains more than 95% of the subsampled data variance (88 and 85% for full-resolution ascending and descending data, respectively, excluding the region around the Papatea block), involves slip along multiple fault segments with a combination of strike-slip and reverse faulting (Fig. 5 and fig. S5). The model gives a total moment equivalent to a \(M_w 7.9\) earthquake, using a shear modulus of 30 GPa, consistent with the global estimates of \(M_w 7.8\), although the moment tensor based on the geodetic inversion shows a larger strike-slip component than that estimated from global seismology data (Fig. 5B). In the epicentral region, we obtained up to 6 m of dextral and reverse slip at depths of ~5 to 25 km on the Humps fault zone and Hundalee fault, with 2 to 3 m near the surface compatible with the field observations. In total, the cumulative moment from the faults in North Canterbury equates to a \(M_w 7.5\) earthquake. Near the coastal end of the Hundalee fault, discontinuities observed in the InSAR data suggest a more north-south trending fault running between the Hundalee and Hope faults. Here we estimate ~1.5 m of mostly reverse slip extending over much of the modeled fault plane. On the seaward part of the Hope fault, we predict localized slip of almost 8 m in the upper 3 km, with 2 m of slip at depth. However, limited data and local inelastic effects make this poorly constrained. The 3D displacements (Fig. 4) and field data

\(\text{Fig. 3. Observed, modeled, and residual interferograms for ALOS-2 and Sentinel-1A data.} \) These images are based on the best-fit model shown in Fig. 5. Heavy black lines indicate the fault patches modeled to have slipped during the earthquake. LOS, line of sight.
acquired in the vicinity show no more than 0.2 m of horizontal displacement on this portion of the Hope fault, which indicates that our inversion is allocating too much shallow slip to the seaward portion of the Hope fault. To the north, where the largest fault offsets are observed in the field, we estimate up to 25 m of strike-slip and 9 m of reverse slip along the Jordan thrust and Kekerengu fault at depths ranging from 10 to 25 km, decreasing to ~10 m near the surface. Along the submarine Needles fault, we estimated strike-slip of up to 10 m in the upper 10 km, with shallow reverse slip of ~5 m (fig. S5). In summary, the rupture propagated through two distinct tectonic domains separated by a major left-stepping discontinuity centered on the Papatea block. Our slip model for crustal faults indicates that faults in the North Canterbury domain have a greater reverse component and yield an average rake of 130° compared with those of the MFS, which have greater dextral slip with an average rake of ~160°.

Discontinuities in the InSAR data and field observations indicate that a number of smaller fault strands, including the London Hills and Fidget faults, also slipped during the rupture (Fig. 1). We estimated ~1.5 m of right-lateral slip and 2 m of reverse slip along the London Hills fault at Cape Campbell. Along the Fidget fault, where clear discontinuities can be observed in the ALOS-2 descending interferogram and in ground observations, we obtained slip of ~6 m at a depth of ~10 km, which alone equates to a $M_w$ 7.1 earthquake.

Given the proximity of the event and the location of the southern end of the Hikurangi subduction zone, it is possible that some of the deep slip could be a result of slip on the interface, which is located ~25 km beneath Kaikōura. To quantify the amount of slip that may have occurred, we include an additional source to represent the subduction interface. The interface is modeled as a single plane that approximates the location of the subduction geometry in the area (19). To prevent large increases in moment from unrealistic slip on offshore regions of the interface not constrained by the data, we add a moment constraint to the inversion, limiting the total moment to $M_w$ 7.9 (assuming a shear modulus of 30 GPa). Although the addition of a subduction source does not significantly change the total misfit (<1%), it is able to reproduce some of the subsidence inland, which cannot be done by the crustal model alone, and the moment tensor is more similar to global moment tensor solutions (Fig. 5). However, because of trade-offs between slip on the crustal faults and the interface, the model introduces some larger misfits in the nearfield around the Kekerengu fault. The interface model predicts reverse slip of ~4 m at the base of the crustal faults inland of Kaikōura, extending to the north where it decreases to ~1 m (Fig. 6). On the crustal faults, the overall pattern of slip stays the same, with maximum slip occurring along the Kekerengu segments. Across all of the modeled crustal faults, slip is generally shifted to shallower depths, resulting in a decrease of ~4 m between 15 and 25 km depth and an increase, most notably on the Jordan thrust and Kekerengu faults, of 3 to 4 m in the upper 10 km (Fig. 6D). Although the interface source helps to explain the observed farfield subsidence and non-double-couple components of global moment tensors, the majority of moment is being generated by slip along the crustal faults (table S2). In the case for which we constrain the moment to $M_w$ 7.9, the contribution of the interface source is ~15%. This drops to 2% if the magnitude is limited to $M_w$ 7.8 but increases to 29% in the case of $M_w$ 8.0.

With the use of both best-fitting source models described above, we modeled the tsunami wave field and compared it with the time series from marigrams from tide-gauge stations at Kaikōura, Castlepoint, Wellington, and Christchurch (fig. S3). We applied the COMCOT (32) tsunami model, which calculates the tsunami wave-field propagation on a set of staggered regular grids to solve the linear and nonlinear shallow-water wave equations. The relevant grid resolution was 0.5° in longitude and a maximum of 0.4° in latitude. This source model satisfactorily explains the travel times to the individual tide-gauge stations but shows discrepancies in wave amplitudes and wave phases (fig. S3). Amplitudes are generally too small, particularly for the Wellington and Christchurch marigrams: The amplitude mismatch is a factor of 10 for Wellington and a factor of 5 for Christchurch. Kaikōura and Castlepoint show a much better amplitude match (less than a factor-of-2 mismatch). The observed mismatch may be due to local effects around the tide gauges (Wellington tide gauge, for example, is located inside the Wellington Harbor) or a lack of detail in the bathymetry grids used for the simulation or may indicate additional offshore deformation due to fault movement not identified in the inversion of onshore deformation. Alternatively, the contribution of horizontal displacements to the displacement of topography may be particularly important when there is such a large strike-slip.
component of slip (33). Notably, there is very little difference to the data fit when using either the crustal fault model or the model with an interface source. Because all of our currently available observations are onshore, both inversions produce very similar patterns of uplift, which ultimately drive the tsunami simulations. A possible explanation is that we are missing slip offshore, which we are unable to constrain with our subaerial observations alone.

Discussion and conclusions

The $M_w$ 7.8 Kaikōura earthquake clearly demonstrates that fault systems can undergo ruptures involving slip along numerous faults with diverse orientations, slip directions, and degrees of mechanical linkages. Geometric complexities have been suggested as a major control on the termination of a rupture (1–3). The exceptional rupture complexity during the Kaikōura earthquake, including apparent stepovers of 15 to 20 km, would not have been considered as a plausible scenario in seismic hazard models. Moreover, the complex nature and lengthy propagation of the rupture hampered accurate early magnitude determination and would have posed issues for conventional earthquake early warning systems. Whereas the faults to the north—including the Needles, Kekerengu, Jordan thrust, and Upper Kowhai faults—form a reasonably continuous structure, the distance between the Humps and Hundalee faults in the epicentral region and the Upper Kowhai and Hope faults is ~15 km. This gap coincides with a change from more reverse faulting in the south to predominantly strike-slip in the north and is more than double the distance usually assumed as the limit for halting a fault rupture in standard seismic hazard models. The 2010 $M_w$ 7.2 El Mayor–Cucapah earthquake in northern Mexico ruptured across a 10-km stepover in the surface faults, but gradients in optical pixel offsets and InSAR data indicated that slip continued at depth (7, 34). During the Kaikōura earthquake, slip along the interface could also act as a linking structure at depth. However, models suggest that any slip on the interface was too far downdip to link the Humps and Hundalee faults with the faults to the north. InSAR observations and subsequent field evidence suggest the existence of previously unmapped, north–south striking faults that run between the Hundalee and Upper Kowhai fault (Fig. 1), which might act as a transfer fault linking the two structures (Figs. 4 and 5). Given the variability in fault orientations, it is possible that this rupture could be explained by the keystone fault hypothesis whereby interlocking complex fault networks enable differential stresses to rise beyond the limit defined by optimally oriented faults, allowing a rupture to spontaneously propagate through an array of faults with a range of orientations (9). However, identifying which of the faults is the keystone fault will require further work. Regardless of the rupture mechanism and considering the incompleteness of many global fault databases, which typically show only surface faults, these observations highlight the need to account for larger jumps in hazard models, which may be accommodated by unmapped faults or dynamic triggering (5, 6, 35).

Based on the location of the epicenter in the south and peak slip occurring much further north on the Kekerengu fault, it is clear that the rupture initiated in the south and propagated north. We suggest that the earthquake’s northward propagation onto numerous faults was the result of static stress changes imposed by the earlier stages of the rupture, although dynamic stressing may also have played a role (34). Using only the fault slip from the Humps and Hundalee faults in the south, we calculated positive static stress changes (29) over much of the Upper Kowhai fault and Jordan thrust up to ~0.75 MPa (Fig. 7). Large negative stress changes are predicted along much of the modeled Hope fault. Localized areas of positive stress changes are modeled near the inland portion of the Hope fault, in addition to the offshore seaward end. We also assessed stress changes on the northernmost faults (Kekerengu and Needles), which are attributable to slip on the Upper Kowhai fault, Jordan thrust, and other faults further south. This indicates that the upper 10 to 15 km of the Kekerengu fault was loaded by more than 2 MPa in regions where we estimate the largest coseismic slip. As a result of stressing by the Humps and Hundalee segments, large stress increases are also predicted in the area of maximum slip near the base of the Jordan thrust (Fig. 6). When all crustal faults were used to stress the interface source, large regions of increased stresses were found, including an area offshore between Kaikōura and the Papatea fault consistent with the location of a cluster of aftershocks (Figs. 1 and 7 and fig. S1). Forward stressing of fault segments along the Kaikōura coast may have played an instrumental role in allowing the rupture to propagate along such a great length of the plate boundary.

Zones of permanent deformation are well documented in the geological record at stepovers in strike-slip fault zones at spatial scales of hundreds of meters or more (36–39). Large misfits to geodetic data observed following large earthquakes have also been explained by the occurrence of inelastic deformation and coseismic ground damage (39). Although our slip models can explain ~95% of the data variance, we are unable to account for a substantial amount of the nearfield deformation. Some of the misfit, particularly in the Humps fault zone in the south, may be due to ground damage, as suggested by the large reduction in coherence (fig. S6) between pre- and coearthquake interferograms. However, the large coherent uplift associated with the Papatea fault...
and the counterclockwise rotation of the Papatea block (Figs. 4 and 8) suggests a substantial component of rigid block motion. Given the complex fault configuration around the uplifted region—which is bounded on the east by the westward-dipping Papatea fault, to the west by the northwestward dipping Jordan thrust, and to the south by the northward dipping Hope fault—it is difficult to fit the observed coseismic deformation using elastic dislocation methods. Based on the magnitude of the observed offset along the Papatea fault, which reaches almost 8 m, when using elastic dislocations one would expect to see at least 4 to 5 m of subsidence on the footwall, yet we observed only tens of centimeters of subsidence. To the west, the uplifted region lies within the footwall of the Jordan thrust, which should have subsided given the 2 to 3 m of uplift...
associated with the Jordan thrust. This demonstrates that dislocation models struggle to reproduce the transfer of coseismic slip through complex fault networks or the asymmetric uplift and subsidence patterns around faults. The fault configuration around the uplifted block, asymmetric uplift pattern (40), and larger-scale MFS are consistent with this structure being part of a pop-up structure within a restraining bend between the Jordan thrust and Kekerengu faults. Furthermore, a semicontinuous GPS installed within the Papatea block within 2 days of the earthquake shows negligible vertical postseismic displacements, and there have been no aftershocks associated with the lineament (Fig. 4). The large right-lateral slip along the Upper Kowhai, Jordan thrust, and Kekerengu faults to the north, compared with the negligible slip on the Hope fault to the south, produces the observed counterclockwise rotation (Fig. 8). The narrowing of the stepover to the south and the presence of the steeply dipping Papatea fault focus uplift along the eastern edge of the block. It is also plausible that the Papatea fault changes dip and merges into the Hope fault and Jordan thrust at shallow depths and that the deformation and uplift of this block is a shallow feature. The magnitude of uplift within the block suggests that these pop-up structures can be created rapidly during large earthquakes. However, given the large coseismic displacements, current topography, and short repeat interval (390 years) for events on the Kekerengu fault and Jordan thrust (41), it is unlikely that this structure is activated during every earthquake. We suggest that much of its growth takes place only during larger multifault ruptures.
such as the 2016 Kaikōura earthquake, which propagate through the restraining stepover. The depths to which faults slip have important implications for seismic hazard. Observations from large earthquakes show an increase in average slip with increasing fault length in excess of the length scale set by the seismogenic thickness (42–44). Though not observed, this would imply higher stress drops for larger events. To reconcile this discrepancy, models have been proposed suggesting deep slip that penetrates the base of the seismogenic layer (42, 43). Many of the faults in the Kaikōura earthquake have substantial modeled slip to depths approaching 25 km, even in the event that 4–5 m slip along the interface is required. These depths are much greater than the rupture depths prescribed in the New Zealand National Seismic Hazard Model (12 to 15 km) (47). Although the resolution of the model will be reduced at depth, tests in which we vary the bottom depth from 15 to 30 km show an increase in the residuals when the bottom depths are less than 25 km. The deeper seismogenic depths that we observe in our best-fitting models may be due to the cooling effect of the subducting Hikurangi slab, which will deepen a thermally controlled brittle-to-ductile transition.

Paleoseismological data are widely used for informing recurrence intervals for individual faults in seismic hazard models (47). However, if an event with this level of complexity would have occurred in the past, it would likely have been interpreted as multiple events, biasing estimates of maximum magnitude and recurrence interval. This interpretation, combined with the large apparent jump between some of the fault ruptures, would preclude the Kaikōura earthquake as a scenario earthquake in even the most well-developed seismic hazard models (30). Although the unprecedented, complex, multifault rupture observed in the 2016 Kaikōura earthquake may be partly related to the geometrically complex nature of the faults in this region, this event emphasizes the importance of reevaluating how rupture scenarios are defined for seismic hazard models in plate boundary zones worldwide.

Materials and methods

We used satellite radar interferometry data, acquired by Sentinel-1 and ALOS-2 satellites, in conjunction with GPS and field uplift to measure the ground deformation associated with the Mw 7.8 Kaikōura earthquake. Range and azimuth offset data were used to derive the full 3D displacement field, which was ground-truthed with campaign and continuous GPS observations. To model the earthquake, we used InSAR phase data along with GPS and coastal uplift measurements to invert for the best-fitting slip distribution. Fault geometries were derived from observations of surface rupture in geodetic data and in the field. We used the best-fitting slip models to generate a tsunami wave field and compared the results with tide gauge locations around the New Zealand coast.

REFERENCES AND NOTES

RESEARCH | RESEARCH ARTICLE


29. See supplementary materials.


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SUPPLEMENTARY MATERIALS

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Supplementary Text

Figs. S1 to S6
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References (45–55)
Data S1 to S4

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Complex multifault rupture during the 2016 $M_w$ 7.8 Kaikoura earthquake, New Zealand

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An earthquake with a dozen faults

The 2016 moment magnitude ($M_w$) 7.8 Kaikoura earthquake was one of the largest ever to hit New Zealand. Hamling et al. show with a new slip model that it was an incredibly complex event. Unlike most earthquakes, multiple faults ruptured to generate the ground shaking. A remarkable 12 faults ruptured overall, with the rupture jumping between faults located up to 15 km away from each other. The earthquake should motivate rethinking of certain seismic hazard models, which do not presently allow for this unusual complex rupture pattern.

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