

COMMENTARY

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Key Points:

- Complex Kaikoura earthquake ruptured subduction interface and produced large surface offsets on crustal strike-slip faults
- Bai et al. (2017) demonstrate that tsunami observations imply coseismic slip occurred on the shallow megathrust
- Combining multiple geophysical observations helps constrain nature of earthquake rupture process

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Reconciling the deformational dichotomy of the 2016 M_w 7.8 Kaikoura New Zealand earthquake

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Abstract Following the 2016 M_w 7.8 Kaikoura earthquake, uncertainty over the nature of the coseismic rupture developed. Seismological evidence pointed to significant involvement of the subduction megathrust, while geodetic and field observations pointed to a shallow set of intracrustal faults as the main participants during the earthquake. The addition of tsunami observations and modeling as reported in Bai et al. (2017) places additional constraints on the specific location of coseismic slip, which when combined with other observations indicates the simultaneous occurrence of shallow slip on the subduction interface and slip on overlying, upper crustal fault structures. This Kaikoura-style earthquake, involving synchronous ruptures on multiple components of the plate boundary, is an important mode of plate boundary deformation affecting seismic hazard along subduction zones.

1. Introduction

On 13 November 2016 (11:02:56 UTC) a large (M_w 7.8) earthquake struck in the sparsely populated region near Kaikoura, New Zealand, on the northern end of the South Island (Figure 1). Because of its occurrence just after midnight (00:02:56, 14 November 2016, local time), there were few immediate, eye-witness reports of the occurrence and extent of surface faulting, although it was immediately known that damage was significant in several town centers and that numerous landslides had blocked highways and the main rail line. The earthquake is located at a fundamental transition along the Pacific–Australia plate boundary through New Zealand—a transition from subduction along the Hikurangi subduction zone, to the north, to a plate boundary characterized by dominantly strike slip and oblique strike-slip plate motion along the Alpine Fault system, to the south. Between the Hikurangi subduction zone and Alpine Fault, the Alpine Fault system splays into a set of major strike-slip faults (Marlborough Fault system; Figure 1), whose north-eastern extents run through the epicentral and aftershock region. This location, where both a subduction plate boundary and upper crustal faults coexist, has led to uncertainties in the fundamental nature of the earthquake—was it a subduction plate interface earthquake (a megathrust such as recently in Japan and Chile) or an earthquake limited to the upper crust. The results of Bai et al. [2017] indicate that there was significant fault displacement on what is most likely the subduction interface. These results require that the Kaikoura earthquake involved both subduction and upper crustal faulting.

2. Competing Earthquake Models

Initial analyses of the earthquake based on global seismology data (e.g., the USGS Event Page, URL: earthquake.usgs.gov/earthquakes/eventpage/us1000778i) indicated a relatively low angle, oblique slip thrust fault (Figure 1), with an epicentral depth consistent with its occurrence on the megathrust (subduction plate boundary interface). This initial interpretation was complicated because the epicenter location (the initiation point) for the earthquake is south of the southern limit to subduction (Figure 1). Finite fault models that map fault slip onto assumed fault structures showed that most of the seismic moment release was north of the epicenter in a region where there is definitely subduction of the Pacific plate. With daybreak, the picture became more unclear, as there were numerous extremely large offset (up to 10 m in lateral and vertical directions) surface fault ruptures, many of which showed dominantly strike-slip motion [Litchfield et al., 2016]. This earthquake was not simply a subduction thrusting-style event. Additionally, the aftershocks (Figure 1) immediately after and during the first months following the main earthquake show an approximately equal mix of strike-slip (like the surface faulting) and thrust (like the subduction interface faulting) earthquake mechanisms. Many of the aftershocks in the cluster just south of 42°S latitude are low-angle thrust faults, consistent with earthquakes on a subduction interface. Further complicating the seismotectonic interpretations of the

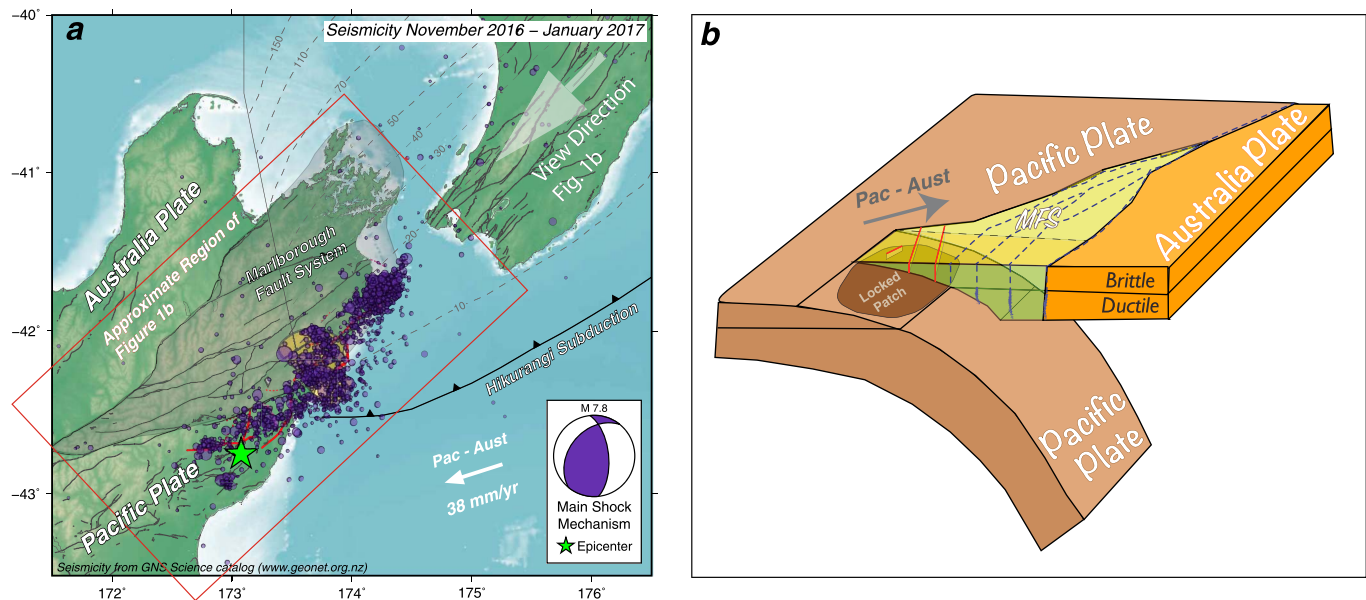


Figure 1. (a) Tectonic setting of the 2016 Kaikoura earthquake and associated seismicity associated. Line running NNW from the southern end of the Hikurangi trench is the inferred southern edge of the subducting Pacific plate (cf. Figure 1b); [Walcott [1998]; Furlong [2007]; Furlong and Kamp [2009]] and dashed lines (labeled in km) running NNE are depth contours for the subduction plate interface. Gray region delineates the area of the Marlborough Fault system, which is a transition zone between the Australia and Pacific plates. The relative plate motion between the Pacific and Australia plates is shown by the white arrow. The green star indicates the epicenter of the main shock. Earthquake locations (blue circles) for aftershocks show the spatial distribution of seismicity associated with the Kaikoura event. The focal mechanism of the main shock (USGS W-phase Moment Tensor) is shown in the inset at the lower right. The yellow shaded region is the approximate megathrust rupture zone from Bai *et al.* [2017]. Crustal faults with major slip during the event are shown in red [from Shi *et al.* [2017]]. (b) Three-dimensional perspective view of the earthquake region. Crustal faults that extend to the base of the upper plate above the subduction rupture zone are those with major slip during the earthquake. (View is from the north as indicated in the arrow in Figure 1a).

event was that the observed extraordinary fault displacements were generally on secondary faults oblique to the orientation of the Marlborough faults (the major faults in the region), some of which were previously unmapped or considered inactive. These active faults are characterized by numerous discontinuous segments with, in some cases, distances of meters to kilometers between fault segments [Hamling *et al.*, 2017; Litchfield *et al.*, 2016]. Within the first day following the earthquake a debate was already underway as to whether this earthquake was a subduction megathrust event on the plate interface or a complex crustal faulting earthquake primarily within the upper plate of the subduction system. This distinction matters beyond the scientific realm, as the implications for changes in the stresses acting on faults elsewhere in the region are potentially different depending on the specifics of the earthquake faulting. How this earthquake may affect future earthquake hazard in the region is dependent on an answer to the fundamental question of its specific characteristics.

3. Reconciling the Earthquake Mechanics

In the months following the earthquake there have been several papers published addressing aspects of this quandary. Various types of geodetic data (GPS, InSAR, and visual satellite imagery) have been used to map the surface deformation and fault displacements (e.g., Figure 1a) [Hamling *et al.*, 2017; Shi *et al.*, 2017; Hollinsworth *et al.*, 2017]. These surface observations are very sensitive to the local, shallow deformation, and the substantial fault offsets seen in the field are faithfully recorded in the suite of geodetic data analyzed. In particular, Hamling *et al.* [2017] developed a model built on geodetic and field observations that could account for most if not all of the observed seismic moment, without invoking slip on the plate interface, but including substantial slip (>20 m in locations) on the deeper extents (10–15 km or deeper) of some of the surface faults. In contrast results from a range of seismological analyses (both using global broadband and array-based band-limited data) found preferred models that placed 50% or more of the seismic moment release on structures likely representing the subduction plate interface [Duputel and Rivera, 2017; Zhang *et al.*, 2017; Hollinsworth *et al.*, 2017]. Although all of these seismology-based models placed substantial fault slip on

a potential subduction-interface surface, they were unable to resolve what happened as the subduction megathrust fault came to the surface. Any slip at shallow levels on the plate boundary would provide strong evidence for this earthquake being at least partly a subduction megathrust.

The paper by *Bai et al.* [2017] provides key answers to that question. Using observations of tsunami propagation after the earthquake, they are able to determine the location and magnitude of tsunamigenic shallow slip associated with the Kaikoura event. Their model involves three main seismic moment producing faults: one (largely strike slip; $M_w \sim 7.3$) in the epicentral region, associated with the initiation of the event; the second (oblique low-angle thrusting) likely located on the subduction interface (indicated in Figure 1a) that ruptures to shallow depths and is a primary tsunami generator ($M_w \sim 7.6$); and the third, representing much of the surface faulting that is oblique strike slip and also generates some seafloor vertical displacements ($M_w \sim 7.6$). Combined, these three generalized fault structures reproduce the observed seismic moment tensor, generate a tsunami consistent with regional observations, and partition the seismic moment release among both the subduction megathrust and shallower crustal faults.

The model of *Bai et al.* [2017] has similarities to models developed in other seismological studies [e.g., *Duputel and Rivera*, 2017], which also invoked multiple faulting structures. The key addition provided by this study is the direct evidence for the location and magnitude of seafloor displacements needed to generate the observed tsunami. These results support the interpretation of the 2016 Kaikoura earthquake as a complex rupture that involved substantial slip (and moment release) on the subduction interface (M_w 7.6), as well as on a suite of upper plate faults (M_w 7.6). One additional constraint placed by the seismology and tsunami analyses, which is not well constrained in the studies of surface faulting, is a constraint on the timing of the moment release and associated fault slip. These results indicate that most of the shallow, crustal faulting occurred synchronously with the rupture on the megathrust. Both sets of large moment release faulting occurred after and north of the initiation site of the earthquake reported by its epicentral location.

Combining the results of these studies using seismological, geodetic, and field observations and related models raises several important issues. First, how common an occurrence are such simultaneous megathrust and upper plate faulting earthquakes? For the Kaikoura earthquake, the locked patch of the subduction zone that ruptured underlies the coastal region of the northern South Island, making any upper plate faulting above that rupture patch observable. More typically, the equivalent coupled parts of subduction systems are offshore, and therefore, any simultaneous shallow crustal faulting that occurs above the rupture patches may not be observable. Second, the seismotectonic interpretation that one gets from combining these different analyses emphasizes the strengths and weaknesses of the various tools earthquake scientists use to infer source characteristics of large earthquakes. Geodetic techniques provide high-resolution constraints on near-surface displacements. However, mapping that surface deformation into fault slip involves model assumptions, and in this case, the shallow faulting dominated the visual and geodetic signal and obscured the deeper slip. Seismologic analyses place robust constraints on the location and nature of seismic moment release but have limited spatial resolution and with the oftentimes relatively low levels of moment release at the shallowest levels of a subduction zone, seismic data alone may provide ambiguous constraints on shallow slip. In a case such as this, in which the crustal faulting and the subduction interface faulting occur simultaneously, the seismological data from the two modes of faulting will be superposed, with the larger amplitude signals (here the megathrust) dominating the analyses. The addition of tsunami observations, which place strong constraints on displacements of the shallow megathrust with other seismological, geodetic, and geological data, helps us to develop integrative models that fully constrain the coseismic fault slip.

4. Discussion

With the results of *Bai et al.* [2017], we can be reasonably confident that the 2016 Kaikoura earthquake involved synchronous or near-synchronous faulting on the megathrust and several overlying crustal faults. However, the conditions that would lead to such behavior are not well constrained. With this well-documented event, a new mode of earthquake behavior in subduction regions must be considered. Here we outline some of the specific aspects of this plate boundary and its faulting and identify some key aspects of the conditions that may allow such earthquakes to occur. For the Kaikoura earthquake, the links between the crustal and plate boundary faulting include (a) the regions of the largest displacement, shallow faulting tend to overlie the regions of the megathrust that experienced the most coseismic slip; (b) the crustal faults

that slipped are not the major faults of the Marlborough Fault system but rather they include numerous short fault segments, often with large distances between the ends of fault segments and with orientations that tend to be more northerly than the Marlborough faults; (c) slip amounts on these surface faults in spots exceed the seismologically determined magnitude of fault slip on the megathrust; and (d) the subducting slab beneath the surface faults that slipped is at a relatively shallow depth (~25 km or less; Figure 1), implying that these upper plate faults are within the brittle deformation zone over their entire depth extent and slip primarily through earthquakes. Any mechanism invoked for this event should account for these characteristics—in particular the synchronicity of the megathrust and crustal faulting [Furlong *et al.*, 2017].

The 2016 M_w 7.8 Kaikoura earthquake produced synchronous faulting on the plate boundary subduction interface—the megathrust—and on a suite of crustal faults above the rupture zone in the overlying plate. Although displacements on some surface faults are extraordinary, particularly considering the short fault lengths and segmented nature of the faults, the results of Bai *et al.* [2017], with its inclusion of tsunami data and modeling, indicate that there was also clearly megathrust involvement with rupture reaching to, or nearly to, the trench. With these results it is clear that the 2016 Kaikoura NZ earthquake represents a mode of subduction zone rupture that must be considered in other regions.

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