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News & Views

How complex is the 2016 M_w 7.8 Kaikoura earthquake, South Island, New Zealand?Xuhua Shi^{a,*}, Yu Wang^a, Jing Liu-Zeng^b, Ray Weldon^c, Shengji Wei^a, Teng Wang^a, Kerry Sieh^a^a Earth Observatory of Singapore, Nanyang Technological University, Singapore 639798, Singapore^b State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China^c Department of Earth Sciences, University of Oregon, Eugene 97403, USA

A powerful earthquake of moment magnitude (M_w) 7.8 occurred in the Kaikoura region, South Island, New Zealand, at 00:02:56 AM (local time), 14 November 2016. According to the Institute of Geological and Nuclear Sciences (GNS) in New Zealand, the earthquake epicenter was at 42.69 °S, 173.02 °E, about 90 km northeast of Christchurch, the 3rd largest city in New Zealand (Fig. 1a). GNS reported a focal depth of 15 km. The main shock of the Kaikoura earthquake sequence lasted about 2 min with the most severe shaking occurring about 50 s after the hypocenter origin time. Four large aftershocks of M_w 6.0–6.5 (Fig. 1b) occurred within 13 h of the main shock according to the United States Geological Survey (USGS). The total number of aftershocks exceeded 2000 by 17 November 2016. The rupture exceeded 150 km (Fig. 1a, b), from south of the eastern Hope fault, northeastward, to Cape Campbell, including ~34 km of offshore rupture along the northeast-trending Needles fault (Ref. NIWA, <http://niwa.co.nz/news/scientists-detect-huge-fault-rupture-offshore-from-kaikoura>).

This powerful earthquake significantly impacted the society and natural environment. Two people died and more than 20 were injured. More than ten buildings were damaged or completely collapsed (Ref. RadioNZ, <http://www.radionz.co.nz/news/national/318002/live-the-quake-aftermath>). Helicopter survey and satellite image analyses indicate that the earthquake triggered as many as 100,000 landslides, which destroyed and/or blocked roads and railways at many places in the eastern part of the South Island. Moreover, coseismic uplift northeast of Kaikoura generated tsunami waves that arrived at Kaikoura about 30 min after the rupture started, with wave heights up to about 1.5 m (Ref. IOA, <http://www.ioc-sealevelmonitoring.org/station.php>).

This earthquake occurred within the tectonically active and complex Australia-Pacific plate boundary system (Fig. 1a). To the north, the Pacific plate subducts beneath the Australia plate along the Hikurangi trench, east of North Island. The motion is nearly orthogonal to the plate boundary in northernmost North Island. To the south, the plate motion progressively shifts to almost purely right-lateral, accommodated by the Alpine fault on the southwest part of South Island. The transition in plate boundary style is centered in the northern part of the South Island, generating the

complicated Marlborough fault system [1] to diffusively accommodate the oblique plate convergence at a rate of ~40 mm/year. The Marlborough fault system includes four major right-lateral strike-slip faults conveying onto the Alpine Fault, from north to south, the Wairau, Awatere, Clarence and Hope faults (Fig. 1a, b). Among these faults, the Hope fault accommodates 20–25 mm/year right-lateral plate motion during the Holocene and is capable of generating ground ruptures at a very short recurrence interval of 180–310 years [1]. The other faults have much slower Holocene rates (i.e. 3–6 mm/year); and average rupture recurrence intervals are 5–10 times longer than the Hope fault [2–4]. Numerous smaller active faults between these major right-lateral faults, with diverse fault orientations and a mixture of reverse and strike-slip motion, form a complex network across the northern South Island (Fig. 1b). This complex fault system has caused several destructive, large, historic earthquakes [1] (Fig. 1b), including the 1848 M_w 7.5 earthquake [5] on the Awatere fault, the 1888 M_w 7–7.3 earthquake [6] on the western Hope fault, and the 1780 ± 60 A.D. M_w 7.2 earthquake on the eastern Hope fault. The most recent earthquake was the 2010 M_w 7.1 Darfield (Canterbury) earthquake [7], which occurred 90 km south of the Kaikoura earthquake's epicenter.

The complicated active fault setting of the transitional plate boundary in the northern South Island may have played a critical role in the extraordinary complexity of the Kaikoura M_w 7.8 earthquake, one of the most complex earthquakes ever recorded on land. First, this complexity is indicated in the point-source moment tensor as reported by USGS (“beach ball” in Fig. 1b), which shows a strong non-double-couple solution. The possible fault plane strikes approximately parallel to the coastline and dips 38° to the northwest. Second, analyses from interferometric synthetic aperture radar (InSAR) images (Ref. COMET-NERC, <http://comet.nerc.ac.uk>; GSI, <http://www.gsi.go.jp/cais/topic161117-index-e.html>), compared with field investigations by GNS Science (Ref. GeoNet, <http://info.geonet.org.nz/pages/viewpage.action?pageId=20971550>), New Zealand, demonstrate that the earthquake ruptured at least 12 major fault sections (Fig. 1b) (Ref. <https://info.geonet.org.nz/display/quake/2016/12>), including several that were previously unidentified. Interestingly, the rupture initiated south of the eastern Hope fault and then propagated northeastward along several faults, including the Hope, Uwerau, Jordan thrust, Papatea, and Kekerengu faults on land, and continued along the offshore Needles fault (Ref. NIWA, <https://niwa.co.nz/news/>

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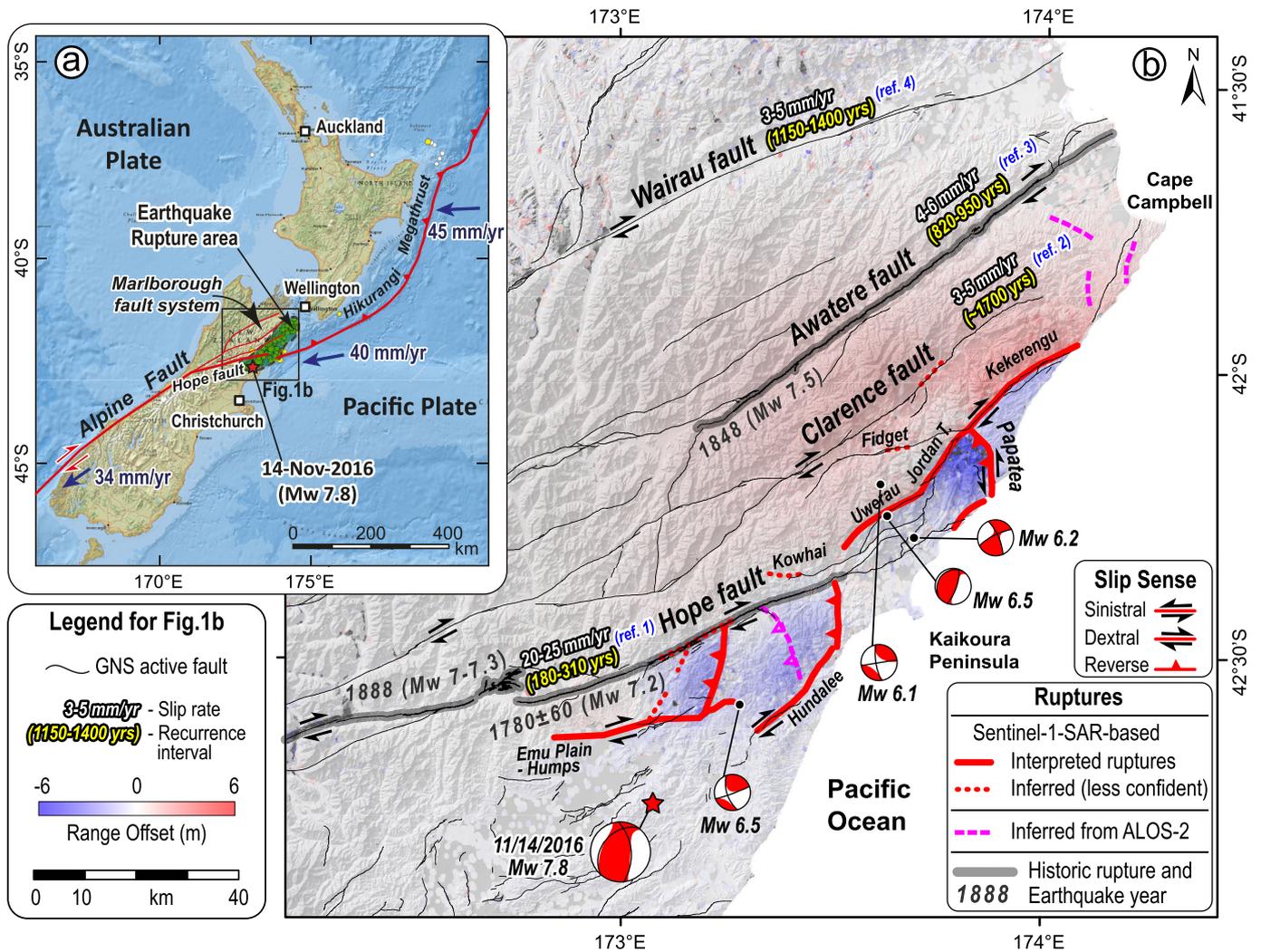


Fig. 1. The tectonic setting and ruptures of the M_w 7.8 Kaikoura earthquake in the northern South Island, New Zealand. (a) The plate boundary system and faults in New Zealand. Plate rate vectors are relative to the Australian plate. Map source: USGS. (b) Rupture interpretation based on Sentinel-1 SAR and ALOS-2 data (GSI, <http://www.gsi.gov.jp/cais/topic161117-index-e.html>). The color-coded range offset image is produced and provided by John Elliott and Tim Wright from COMET-NERC (<http://comet.nerc.ac.uk/>). Also shown are Holocene slip rates and earthquake recurrence intervals for the four major right-lateral strike-slip faults in this region. Historic ruptures and earthquake years are based on Langridge et al. [1].

scientists-detect-huge-fault-rupture-offshore-from-kaikoura) to near Cape Campbell (Fig. 1b). The sense of slip on these surface-rupturing faults include right-lateral (Humps, Hope, Hundalee, Kekerengu and Needles faults), left-lateral (a newly identified fault east of the Papatea fault), and reverse or oblique (Jordan Thrust and Papatea). The earthquake seems to have started on a set of widely-spaced sub-parallel faults in the south, including a portion of the Hope fault, and then jumped through a series of closely-spaced faults to the Jordan Thrust-Kekerengu-Needles faults. Such complex behavior suggests a three-dimensional accommodation of the plate boundary transpressional shear across the region. The Kaikoura earthquake appears to be much more complex than the historic earthquakes in this region that are believed to have ruptured only single fault segments [1] (Fig. 1b). Although the 2010 M_w 7.1 Darfield earthquake also ruptured several adjacent faults with different senses of fault slip (dextral, sinistral and reverse) [7], it did not exhibit long-distance jumping like the M_w 7.8 Kaikoura earthquake (Fig. 1b). More globally, the rupture of the Kaikoura earthquake is comparably with, or more complex than the 1992 Landers M_w 7.3 earthquake in southern California [8], the 2002 M_w 7.9 Denali earthquake in Alaska [9], the 2001 M_w 7.8

Kokoxili earthquake [10], the 2008 M_w 7.9 Wenchuan earthquake in western China [11], and the 2010 M_w 7.2 El Mayor-Cucapah earthquake in Mexico [12]. All these events manifested complex multi-fault ruptures and their jumping from one fault to another.

Field reconnaissance on surface ruptures by the GNS team of New Zealand showed that the Kaikoura earthquake produced very large coseismic offsets. Along the eastern Kekerengu fault, horizontal coseismic displacements reach up to 11 m [13] (Ref. GeoNet, <http://info.geonet.org.nz/pages/viewpage.action?pageId=20971550>). These measurements are larger than the maximum coseismic horizontal slips of the 2002 M_w 7.9 Denali earthquake (8.8 m) [9] and the 2008 M_w 7.9 Wenchuan earthquake (6.3 m) [14], and are close to the maximum coseismic left-lateral slip of ~ 11.4 m produced by the 2013 M_w 7.7 Balochistan, Pakistan earthquake [15]. Meanwhile, the oblique slip offshore induced 1–3 m of coastal uplift from Kaikoura peninsula to Cape Campbell (Ref. GeoNet, <http://info.geonet.org.nz/>) (Fig. 1b).

Understanding the cause of the extraordinary complexity of the M_w 7.8 Kaikoura earthquake will provide important perspectives for the study of earthquakes and seismic hazard assessment in regions with complex fault systems (e.g., New Zealand, southern

California, and the Shan Plateau in Southeast Asia). First, this earthquake again challenges the estimation of maximum earthquake magnitude from a single fault segment, or from only closely-spaced active fault traces in seismic hazard analysis. This is because the rupture of the Kaikoura earthquake was far too complex to have possibly been predicted, even if we knew all the previously unrecognized faults in the system. Second, the complex fault ruptures and geometry of the Kaikoura earthquake will challenge the geophysical community in modeling the spatial and temporal evolution of the rupture, usually guided by the observation of surface deformation and seismic waveform records. Third, the Kaikoura M_w 7.8 earthquake suggests that we may need to reconsider empirical earthquake scaling relationships for regions of complex fault systems, different from previous ones [16]. Finally, although the eastern part of the Hope fault could be inferred to be close to the end of its seismic cycle, given its short earthquake recurrence interval of 180–310 years and that its previous rupture event occurred around 1780 A.D. [1], only a very limited portion of the Hope fault may possibly be ruptured during this M_w 7.8 earthquake (Fig. 1b). The partial rupture of the Hope fault during the Kaikoura earthquake, coupled with the complex multi-fault rupture, raises the important question of how we should reconstruct regional rupture patterns from limited paleoseismological records with sparse chronological constraints on land.

The M_w 7.8 Kaikoura earthquake has also raised scientists' concern about the future seismicity in this region. Analysis of Coulomb stress changes induced by this earthquake warns us that the faults at the southern part of New Zealand's North Island, near Wellington, may be closer to failure than the past (Ref. Temblor, <http://temblor.net/earthquake-insights/mw7-8-earthquake-shakes-new-zealand-causes-tsunami-1762/>). The fact that the Kaikoura earthquake occurred along the comparably smaller Marlborough fault system, instead of the larger Alpine fault on the west of the South Island, may also signal the coming of a great earthquake along this plate boundary fault (Ref. Paul Tapponnier, <http://www.earthobservatory.sg/blog/new-zealand's-earthquakes-may-signal-coming--big-one/>). Moreover, the increase in the number of slow-slip events along the Hikurangi plate boundary (Fig. 1a) underneath the North Island, triggered by the Kaikoura earthquake, has encouraged re-evaluation of the potential of a great megathrust earthquake in this region in the near future (Ref. GeoNet, <http://info.geonet.org.nz/pages/viewpage.action?pageId=20546043>).

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