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Foreshocks and delayed triggering of the 2016 M_W7.1 Te Araroa earthquake and dynamic reinvigoration of its aftershock sequence by the M_W7.8 Kaikōura earthquake, New Zealand

Emily Warren-Smith [a,*], Bill Fry [a], Yoshihiro Kaneko [a], Calum J. Chamberlain [b]

[a] GNS Science, P.O. Box 30-368, Lower Hutt, 5040, New Zealand
[b] Institute of Geophysics, School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand

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ABSTRACT

We analyze the preparatory period of the September 2016 M_W7.1 Te Araroa foreshock–mainshock sequence in the Northern Hikurangi margin, New Zealand, and subsequent reinvigoration of Te Araroa aftershocks driven by a large distant earthquake (the November 2016 M_W7.8 Kaikōura earthquake). By adopting a matched-filter detection workflow using 582 well-defined template events, we generate an improved foreshock and aftershock catalog for the Te Araroa sequence (>8,000 earthquakes over 66 d). Templates characteristic of the M_W7.1 sequence (including the mainshock template) detect several highly correlating events (M_L2.5–3.5) starting 12 min after a M_W5.7 foreshock. These pre-cursory events occurred within ∼1 km of the mainshock and migrate bilaterally, suggesting precursory slip was triggered by the foreshock on the M_W7.1 fault patch prior to mainshock failure. We extend our matched-filter routine to examine the interactions between high dynamic stresses resulting from passing surface waves of the November 2016 M_W7.8 Kaikōura earthquake, and the evolution of the Te Araroa aftershock sequence. We observe a sudden spike in moment release of the aftershock sequence immediately following peak dynamic Coulomb stresses of 50–150 kPa on the M_W7.1 fault plane. The triggered increase in moment release culminated in a M_W5.1 event, immediately followed by a ∼3 h temporal stress shadow. Our observations document the preparatory period of a major subduction margin earthquake following a significant foreshock, and quantify dynamic reinvigoration of a distant on-going major aftershock sequence amid a period of temporal clustering of seismic activity in New Zealand.

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1. Introduction

Large earthquakes are followed by aftershocks, the occurrence rates of which decay with time (Utsu et al., 1995). The highest numbers of aftershocks therefore occur immediately after the mainshock, and event detection using amplitude based methods can be problematic due to overlapping phases of large magnitude events (Peng et al., 2006). Furthermore, in instances where a significant foreshock precedes a larger earthquake, dense aftershocks from the first event may hinder detailed analysis of mainshock pre-cursors. In such cases, aftershock (and foreshock) catalog completeness is vital for both theoretical understanding (e.g. of triggering processes and post-seismic deformation) (Kilb et al., 2000) and science response (e.g. providing accurate seismic hazard forecasts following an event) (Ogata and Katsura, 2006).

Application of the matched-filter (or waveform correlation) method to aftershock sequences (e.g. Peng and Zhao, 2009) has resulted in the retrospective detection of many more earthquakes. This method detects events using *a priori* earthquake waveforms as templates, which are cross-correlated with continuous data to search for similar waveforms (Gibbons and Ringdal, 2006). Although such catalogs are still typically missing some early events in sequences, they can produce over an order of magnitude more detections than amplitude based methods alone (Frank et al., 2017; Warren-Smith et al., 2017).

Here we consider the September 2016 Te Araroa earthquakes in northeast New Zealand (Fig. 1), a complex offshore sequence including a M_W7.1 mainshock preceded 18.5 h earlier by a M_W5.7 foreshock. We analyze the temporal and spatial evolution of the sequence using a matched-filter detection routine to identify many events missing from the national catalog (Section 2.1). By computing precise cross-correlation derived phase arrivals, we calculate relative locations between key sequence events. Comparison of individual template responses, especially templates characteristic

* Corresponding author.
E-mail address: e.warren-smith@gns.cri.nz (E. Warren-Smith).

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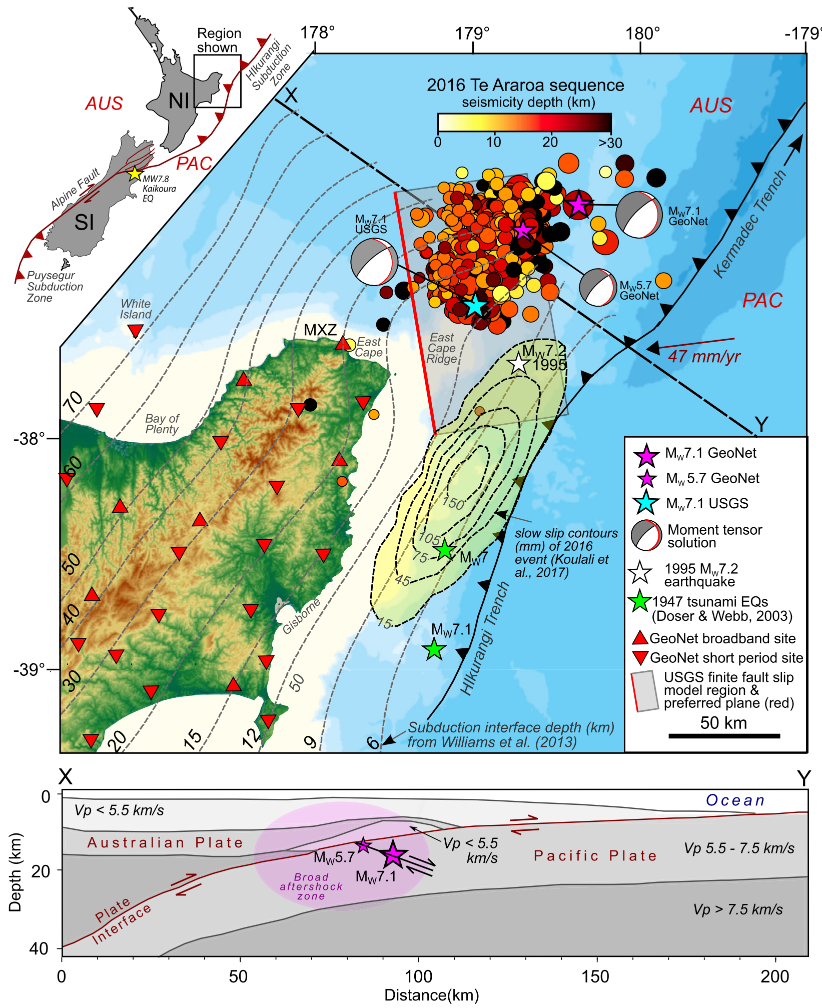

Fig. 1. Top: Overview of 582 GeoNet derived template locations from the Te Araroa sequence. Circles show seismicity colored by depth. Locations of the M_W7.1 and M_W5.7 foreshock from GeoNet are shown with pink stars, the global CMT mainshock location is shown with a cyan star. Moment tensor solutions are shown with the preferred plane in red. The grey shaded box represents the USGS finite fault model for the mainshock rupture patch. Dashed grey lines show the subduction interface contours from Williams et al. (2013). Dashed black lines and yellow shading shows the slip contours from the 2016 slow slip event (Koulali et al., 2017). Upright and inverted red triangles show the GeoNet broadband and short-period stations used respectively in this study. Corner inset shows tectonic setting of East Cape along the Australia (AUS) – Pacific (PAC) plate boundary zone. NI is North Island, SI is South Island. Bottom: Structural cross-section along line X–Y (top panel), showing tectonic setting of Te Araroa sequence. Plate model is based on the 2D velocity model along line RAU07-03 from Bassett et al. (2010). A low velocity (3.5 km/s < Vp < 5.5 km/s) zone of underplated sedimentary and crustal material immediately overlies the location of the Te Araroa sequence, which occurred within the subducting Pacific slab.

of the later mainshock sequence, allows us to test potential triggering mechanisms that led to the M_W7.1 Te Araroa earthquake (Section 3.4).

The Te Araroa sequence was followed by the M_W7.8 Kaikōura earthquake on 14th November 2016, ~800 km to the southwest in north-eastern South Island (Hamling et al., 2017; Kaiser et al., 2017) (Fig. 1). These two 2016 M7+ earthquakes represent the latest major events occurring amid a decade of significant earthquake impacts in New Zealand, following the 2009 Dusky Sound, 2010–2011 Canterbury, and 2013 Marlborough earthquakes. We extend our matched-filter study to quantify the interaction between high dynamic stressing from passing Kaikōura surface waves and the progression of the aftershock sequence of the Te Araroa earthquake.

1.1. Northern Hikurangi seismicity and Slow Slip Events (SSEs)

The Hikurangi subduction zone lies at the southern end of the Tonga-Kermadec subduction system and accommodates near-orthogonal underthrusting of the Pacific plate beneath the Australian plate at a rate of ~60 mm/yr in the Te Araroa region (Beavan et al., 2002) (Fig. 1). The northern Hikurangi margin exhibits a diverse range of interrelated seismogenic phenomena, including shallow slow-slip events (SSEs) (Wallace and Beavan, 2010), large M > 7 tsunami earthquakes (Doser and Webb, 2003; Bell et al., 2014), microseismicity (Delahaye et al., 2009) and tectonic tremor (e.g. Todd and Schwartz, 2016). Previously documented major events include two M_W6.9–7.1 tsunami earthquakes in 1947 on the subduction interface, near shallowly subducted seamounts (Doser and Webb, 2003), resulting in slow velocity ruptures, and subsequent large tsunami (Bell et al., 2014). More recently, a shallow (12 km) M_W7.2 event occurred in 1995, to the south of the Te Araroa sequence, and a deeper (33 km) M_W7.1 event occurred close to the trench in 2001, followed by a M_W6.6 event three months later, close to the September 2016 epicenter (www.geonet.co.nz).

Northern Hikurangi SSEs occur repeatedly every 18–24 months, typically last for a few weeks and exhibit large (>10 cm) displacements. The Te Araroa sequence was preceded in August 2016 by a SSE with >15 cm of slip centered ~70 km offshore, and extending farther north than previously observed events, as far as East Cape (Koulali et al., 2017) (Fig. 1). Mapping the northernmost ex-

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