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Earthquake and Tsunami Potential of the Hikurangi Subduction Thrust, New Zealand

Insights from Paleoseismology, GPS, and Tsunami Modeling

ABSTRACT. The Hikurangi subduction margin, where the Pacific Plate subducts beneath the North Island of New Zealand, poses a major seismic and tsunami hazard to the New Zealand region, but its seismic and tsunami potential is largely unknown because of New Zealand's short (< 170 years) historical record of seismicity. This article discusses the implications of results from GPS, paleoseismology, and tsunami modeling studies for understanding Hikurangi subduction earthquake and tsunami potential. Paleoseismic and geodetic data indicate that earthquakes of M_W 8.0 and larger are certainly plausible at the Hikurangi margin. Paleoseismic evidence for large megathrust earthquakes beneath Hawke Bay in central Hikurangi demonstrates that large seismic slip may occur within an area that currently slips in episodic slow slip events. This result has important implications for seismic hazards at subduction margins elsewhere. Strong similarities between the subduction zones of the Hikurangi margin and the Japan Trench suggest that a giant M_W 9.0 earthquake similar to the 2011 Tōhoku-Oki earthquake may be possible for the Hikurangi margin. Such an event would generate a large tsunami that would inundate much of the east coast of the North Island. Understanding of the earthquake potential of the Hikurangi megathrust is only in its infancy, and we recommend a number of studies to increase knowledge.

INTRODUCTION

Subduction zones, where one tectonic plate dives or "subducts" beneath another, produce the largest and most devastating earthquakes and tsunamis on Earth—the March 2011 Tōhoku-Oki M_W 9.0 earthquake is a striking example. Although many subduction zones have produced great earthquakes ($M_W > 8.0$) in recorded history, the seismic and tsunami generation potential of many others is unknown (e.g., McCaffrey, 2008). Determining earthquake and tsunami potential for subduction zones worldwide is imperative to assess the hazards posed by these important plate boundary features. This goal is hampered by the short historical record of seismicity at many subduction zones. Thus, we must rely on additional data sets to improve our understanding of subduction earthquake potential, including paleoseismological and paleotsunami studies and geodetic studies of subduction interface slip behavior, among others.

Westward subduction of the Pacific Plate beneath the eastern North Island of New Zealand occurs at the Hikurangi subduction margin at rates of 2–6 cm yr^{-1} (Wallace et al., 2004; Figure 1). Understanding of the seismic and tsunami hazard posed to New Zealand by the Hikurangi subduction zone is limited due to the short historical record of earthquakes in New Zealand, spanning only the last ~ 170 years. During that time, only moderate ($M_W < 7.2$) subduction interface earthquakes have been recorded (Figure 1; Webb and Anderson, 1998; Doser and Webb, 2003). However, data from an extensive network of campaign and continuously recording GPS sites on the North Island reveal the contemporary slip behavior of the Hikurangi subduction thrust, including evidence for interseismic coupling on the subduction thrust and the occurrence of slow slip events (Darby and Beavan, 2001; Wallace et al., 2004; Wallace and Beavan, 2010). Moreover, recent paleoseismological and paleotsunami studies along the east coast of the North Island have produced evidence for prehistoric earthquakes that are likely to have occurred on the subduction thrust (Cochran et al., 2006; Hayward et al., 2006; Clark et al., 2011).

In this paper, we bring together available geological and geophysical observations to better understand the future seismic potential of the Hikurangi subduction thrust. We use these data to inform models of tsunamigenesis to evaluate the role that subduction thrust can play in the generation of large tsunamis. We compare the Hikurangi margin with the northern Japan plate boundary to address whether or not earthquakes similar to the March 2011 M_W 9.0 Tōhoku-Oki earthquake are possible in New Zealand. We also discuss future research directions that are needed to better understand the seismic and tsunami potential of the Hikurangi subduction thrust.

HISTORICAL SUBDUCTION EARTHQUAKES AND TSUNAMIS AT HIKURANGI

The historical record of earthquakes and tsunamis in New Zealand is relatively short, with written records extending back only 150–200 years (unpublished data courtesy of Gaye Downes, GNS Science, Lower Hutt, New Zealand, 2011). References to earthquakes and tsunamis are also found in Maori oral history (McFadgen, 2008), though it is difficult to associate them with specific dates and locations or to correlate the events with particular faults. Here, we review candidates for Hikurangi subduction interface earthquakes larger than M_W 7.0 in written and oral historical records. All other confirmed or suspected Hikurangi subduction interface earthquakes in the historical record (not discussed here) are small to moderate magnitude events (e.g., $M_W < 7.0$; Figure 1, see discussion in Wallace et al., 2009a).

The largest well-documented Hikurangi subduction interface earthquakes were the March 25, 1947, Poverty Bay (M_W 7.0–7.1) and May 17, 1947, Tolaga Bay (M_W 6.9–7.1) earthquakes (Figure 1, see PB and TB) at the northern part of the Hikurangi subduction zone. These events share many characteristics of "tsunami-earthquakes" (Kanamori, 1972), such as low felt-intensity shaking (intensity MM4 and MM6 [MM = Modified Mercalli], respectively), long duration, low M_L (5.9 and 5.6, respectively; M_L= local magnitude) relative to M_W (M_W = moment magnitude), large tsunamis relative to the earthquake magnitude, and shallow epicenters (< 10 km) on the subduction thrust near the trench (Downes et al., 2000). The epicenter of the March event is located over a subducting seamount identified in seismic reflection data, and the epicenter of the May event also appears to be associated with a subducting seamount (Bell et al., 2010).

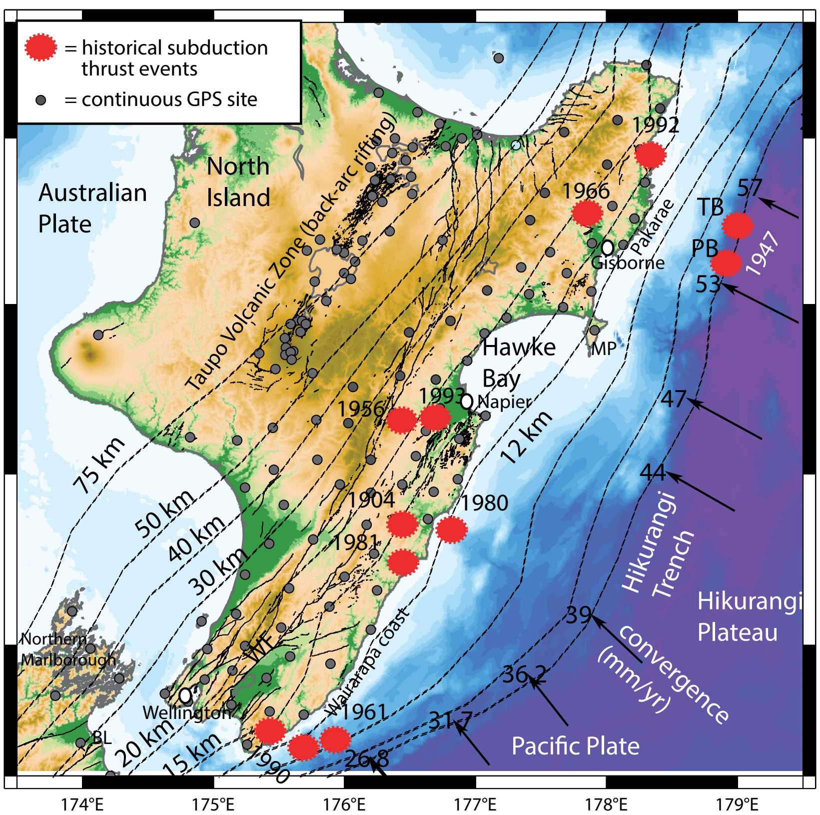

Figure 1. Tectonic setting of the Hikurangi subduction zone at the boundary between the Pacific and Australian Plates. Black contours show the depth to the subduction interface (Williams et al., 2014). Red dots = historical subduction thrust events (all $M_W < 7.2$). Gray dots = continuous GPS sites (http://www.geonet.org.nz). Arrows show convergence rates at the trench in mm yr^{-1} (Wallace et al., 2012a). PB = 1947 Poverty Bay earthquake. TB = 1947 Tolaga Bay earthquake. WF = Wairarapa Fault, the site of the 1855 earthquake. BL = Big Lagoon. MP = Mahia Peninsula. Black lines onshore are active faults (http://www.data.gns.cri.nz/af). In the forearc, most of these faults are either right lateral strike-slip or reverse. The strike-slip faults help to accommodate the margin-parallel component of relative plate motion.

The tsunami that followed the March event reached the coast ~ 30 minutes after the earthquake and affected ~ 120 km of coastline. The largest runup heights of 10–11 m (Downes, 2011) were observed approximately 20 km northeast of Gisborne (Figure 1). Damage included the dislocation of a wooden bridge over the main road near Pouawa that was swept 800 m inland. Fortunately, there were no casualties, largely a consequence of the sparse population of the affected coast. The May earthquake produced a slightly smaller tsunami whose greatest effects were felt farther north than those of the March event. The maximum recorded runup was 6 m ~ 45 km northeast of Gisborne. The coast near Gisborne was probably also affected by a local-source tsunami in 1880 following an earthquake that was gently felt (Downes, 2011; Power and Tolkova, 2013), though details of this event are very limited, and it is not possible to be sure that the earthquake occurred on the subduction interface.

The 1855 Wairarapa earthquake (M_W 8.2), which occurred on January 23, produced a tsunami with maximum observed runups of 10 m approximately 40 km east of Wellington. In total, 300–500 km of coastline was affected, runups of 4–5 m were widespread around Wellington and on the northern Marlborough coast, and the Rongotai Isthmus in Wellington was reportedly overtopped (Grapes and Downes, 1997). The earthquake occurred primarily on the Wairarapa Fault (Figure 1), which is believed to splay from the subduction interface at a depth of about 20–30 km (Henrys et al., 2013). However, based on coastal subsidence data, it is possible that a portion of the subduction interface down dip of the Wairarapa Fault ruptured during the earthquake (Beavan and Darby, 2005), raising the possibility that the 1855 earthquake also involved subduction interface slip.

A possible candidate for a major subduction interface earthquake recorded in Maori oral history is the Hao-whenua earthquake estimated to have occurred in approximately the year 1460 (King et al., 2007; Downes, 2011). Geological evidence and Maori oral history suggest that this event caused uplift in the Wellington region, one consequence of which was closure of a sea channel that was previously used to cross the Rongotai Isthmus by canoe (King et al., 2007; McFadgen, 2008). The name, which translates to "land-swallower," suggests that this event may have been accompanied by a tsunami.

Paleoearthquake and Paleotsunami Studies

At subduction margins where historical records are short (< 200 years) and recurrence intervals of great earthquakes are long (> 300 years), geological records have been useful for providing physical evidence of great earthquakes and tsunamis, estimating recurrence intervals of such events, observing their vertical deformation patterns, and demonstrating variability in magnitude and spatial extent (e.g., Clague, 1997; Cisternas et al., 2005; Sawai and Nasu, 2005; Shennan and Hamilton, 2006; Satake and Atwater, 2007). For example, along the west coast of North America and Canada, paleoearthquake and tsunami studies have revolutionized scientific understanding of the Cascadia subduction zone and the hazard it poses. We aim to achieve a similar level of insight into the Hikurangi subduction zone in the future, but we do not yet have the spread of sites or the tight age control required to produce robust Holocene earthquake histories for different segments of the Hikurangi margin. Instead, we present existing onshore paleoearthquake and tsunami records to illustrate what correlations can be made along the margin that may represent great subduction earthquakes (Figure 2).

> "Improving the paleoseismic record for the Hikurangi margin is of utmost importance if we are to discern the magnitude, frequency, and locations of past Hikurangi subduction thrust earthquakes and associated tsunamis."

A key requirement for identifying past rupture of the subduction interface in great earthquakes is to document simultaneous vertical deformation over a wide geographical area. Highly localized vertical deformation can usually be explained more simply by smaller earthquakes on upper plate faults. For this reason, we have been working at numerous sites along the east coast of the North Island of New Zealand to determine Holocene earthquake and tsunami histories and to test for synchroneity. Detection of simultaneous subsidence (in-board) and uplift (out-board) in a transect perpendicular to the strike of the subduction thrust and at an appropriate wavelength is one strategy for pinning vertical deformation of the upper crust to movement on the interface as opposed to upper plate faults (or in addition to, and simultaneously with, movement of upper plate reverse faults that splay from the subduction interface). The position of the coastline of the eastern North Island relative to the interface makes it most likely to be uplifted in a subduction earthquake. However, the indentation of Hawke Bay (Figure 1) puts a small segment of coastline into the coseismically subsiding zone, providing an opportunity to correlate events across the margin as well as along it (e.g., sites 5, 6, 7 in Figure 2; Cochran et al., 2006).

Figure 2 shows that the most widespread evidence for coseismic

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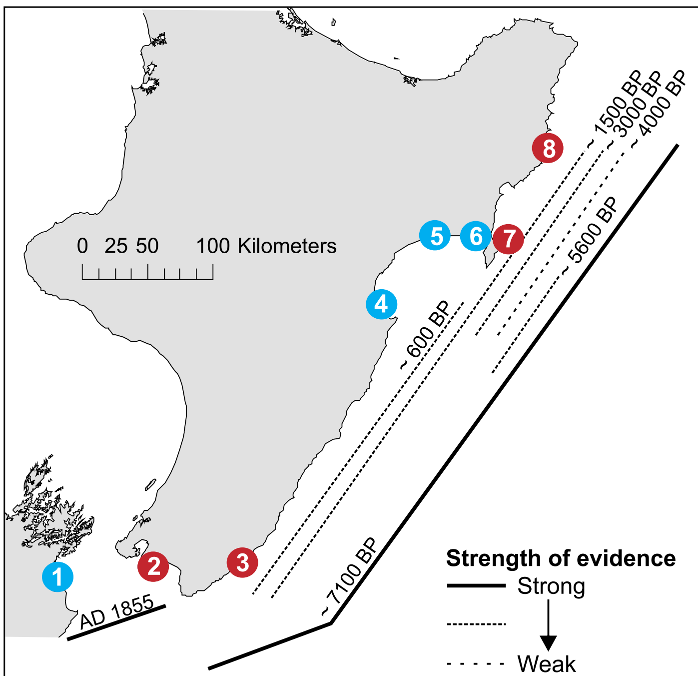
deformation occurred about 7100 BP (calibrated years before present) with sites from the south coast of the North Island through to Pakarae (site 8) in the north recording uplift or subsidence and tsunami inundation. Sudden subsidence is recorded at this time at in-board Hawkes Bay sites 4, 5, and 6, while uplift is recorded at out-board sites 7 and 8 (Figure 2). Given the clustering of ages around 7100 BP, the along-margin extent of evidence, the occurrence of paleotsunamis at some of the sites, and the pattern of subsidence and uplift across the margin, this is our strongest candidate for occurrence of a great Hikurangi subduction earthquake (probably also involving rupture of upper plate faults). There is also evidence for coseismic vertical deformation at multiple sites at about 5600, 4500, 3000, 1600, and 600 BP (Figure 2). However, evidence for the occurrence of great subduction earthquakes at these



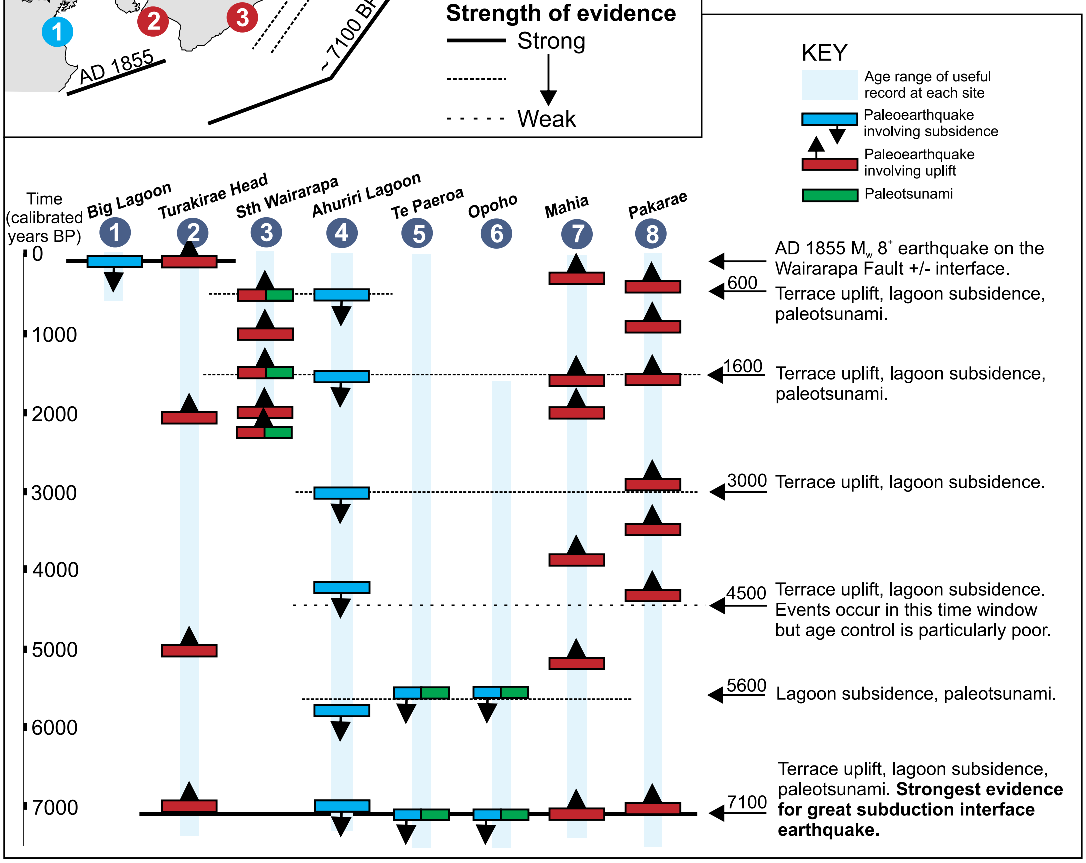


Figure 2. Map in upper panel shows locations of published Holocene records of coseismic vertical deformation along the Hikurangi Margin. Timeline in lower panel shows the approximate ages and types of impact found at different sites along the margin (note that this is an overview that does not show individual dates and their errors). We use black horizontal lines on the timeline to indicate times when vertical deformation occurs at multiple sites along the margin (summarized in the right panel of the timeline). These lines are also used on the map to indicate the approximate lateral extent of deformation and the strength of evidence for occurrence of a great subduction thrust earthquake. *Site 1: Clark et al. (2011) and Hayward et al. (2010). Site 2: McSaveney et al. (2006). Site 3: Berryman et al. (2011). Site 4: Hayward et al. (2006). Sites 5 and 6: Cochran et al. (2006). Site 7: Berryman (1993). Site 8: Wilson et al. (2006).

times is not as strong as the evidence at 7100 BP because they have only been identified at a few sites and/or there is limited age control.

A great-earthquake record for the Hikurangi subduction zone is a work in progress. However, if we make the large assumptions that the earthquakes that caused sudden subsidence in Hawkes Bay involved slip on the subduction interface, and that the coincident raising of terraces further out-board occurred in the same earthquakes (see discussion in Cochran et al., 2006), then we can conclude that the Hikurangi subduction thrust has moved in great earthquakes in the past. If we also assume that the scant age control we have for the subsidence approaches the actual timing of past earthquakes, then we start to get a picture of great earthquake recurrence—every 1,000–1,500 years for much of the Holocene. Even if the coseismic uplift and subsidence did not occur in the same earthquakes, our existing evidence indicates they were closely spaced in time so they may represent a sequence of large earthquakes occurring along the margin within a short timeframe (days to decades) with 1,000–1,500 year periods of relative quiescence between the sequences.

GPS Evidence for Contemporary Megathrust Slip Processes

Between megathrust earthquakes, the short-term (interseismic) slip rate close to and across most faults is often considerably less than the long-term slip rate expected from the relative motion of the adjacent tectonic blocks. This phenomenon, caused by friction along the fault and often referred to as interseismic "locking" or "coupling," gives rise to elastic strain rates in the rocks adjacent to the fault that are measurable with GPS methods. Although knowledge of contemporary coupling/locking of subduction interfaces from GPS only captures the last 10–20 years, in many recent examples, the distribution of slip in major megathrust earthquakes agrees extremely well with the locking distribution prior to the earthquake (e.g., Miura et al., 2004; Chlieh et al., 2008; Moreno et al., 2010; Loveless and Meade, 2011; Protti et al., 2014), suggesting that coupling distributions provide a useful guideline for understanding which portions of the interface are prone to seismic rupture. However, it is possible that coupling distributions may vary throughout the interseismic period, and geodetic measurements over multiple earthquake cycles at many subduction zones will be needed to definitively test whether or not geodetic coupling measurements are always useful indicators of future seismogenic slip. Given New Zealand's short historical seismicity record, geodetic measurements of interseismic coupling are one of the few indicators currently available to help us delineate zones of the Hikurangi interface that may be more prone to rupture in great earthquakes.

Much of the Hikurangi margin forearc is subaerial due to subduction of the buoyant Hikurangi Plateau (a Large Igneous Province; Figure 1), making it ideally suited to using GPS measurements to monitor contemporary slip behavior over a large depth range of the megathrust, from < 10 km to > 70 km depth (Figure 1). Over the last 20 years, a network of ~ 1,000 campaign GPS sites have been measuring crustal motion throughout New Zealand (campaign deployments are targeted for a specific experiment over a limited timeframe). Moreover, a comprehensive network of ~ 80 continuously operating GPS sites (i.e., permanent sites) exists along the Hikurangi subduction margin (Figure 1; cGPS data are available at http://www.geonet.org.nz). Crustal deformation measurements derived from these data sets have revealed both the distribution of interseismic coupling (Darby and Beavan, 2001; Wallace et al., 2004, 2012a) and the occurrence of transient slow slip events (SSEs) on the subduction interface (Douglas et al., 2005; Wallace and Beavan, 2010; Wallace et al., 2012b; Wallace and Eberhart-Phillips, 2013; Figure 3).

Interpretation of campaign GPS data (using an elastic block modeling/backslip approach) from the North Island shows that the subduction interface at the southern Hikurangi margin is interseismically coupled to depths of 30–40 km, while there is an abrupt transition to an aseismic creep-dominated interface near ~ 40°S (Wallace et al., 2004, 2012a; Figure 3). We note that the near-trench locking on the shallow interface is not well resolved due to a lack of geodetic measurements offshore. However, large, near-trench earthquakes such as the 1947 tsunami earthquakes suggest that locking near the trench at Hikurangi is highly likely. Episodic slow slip events that we located using observations from the continuous GPS network (Figure 1) mirror the interseismic coupling estimates—the SSEs tend to follow along the downdip edges of interseismic coupling (Wallace and Beavan, 2010), although in some cases the slow slip regions also overlap with the locked regions (Wallace et al., 2012b), suggesting that interface slip behavior is highly heterogeneous in some locations. Slow slip events at subduction zones elsewhere are also typically observed at the transition from interseismic coupling to aseismic creep (Dragert et al., 2001; Schwartz and Rokosky, 2007, and references therein), supporting numerical model results indicating that slow slip events arise from transitional frictional behavior (e.g., conditionally stable in the transition from velocity weakening to velocity strengthening; Liu and Rice, 2005). Thus, SSEs at Hikurangi may also provide useful insights into the potential limits of the seismogenic zone and the location of velocity weakening (stick-slip) vs. velocity strengthening (aseismic slip) behavior. However, we emphasize that GPS measurements only span the last 20 years. Whether or not the slowly slipping vs. locked regions of the interface that we identify with GPS are persistent throughout the interseismic period cannot be known until we have GPS measurements spanning multiple seismic cycles.

Slow slip events at Hikurangi exhibit clear bimodal behavior going from south to north. Southern Hikurangi SSEs are long-lived (1–1.5 years), deep (> 30 km depth), large (slip occurring in the events is equivalent to a M_W ~ 7.0 earthquake), and infrequent (recurring about every five years), while north Hikurangi SSEs are short-lived (2–3 weeks), shallow (< 5–15 km depth), moderate to large (M_W ~ 6.3–6.8), and frequent (every 1–2 years) (Figure 3; Wallace and Beavan, 2010). More recently, Wallace and Eberhart-Phillips (2013) identified smaller, deep SSEs at the central Hikurangi margin (directly down dip of the shallow, short-duration SSEs; Figure 3, dashed contours) that last two to three months and involve smaller surface displacement at continuous GPS sites of a few to several millimeters. The Hikurangi margin has one of the most diverse sets of SSE characteristics of any subduction zone. Moreover, the moment accumulation rate that we determine from interseismic coupling that occurs between slow slip events is ~ 40% higher than the moment accumulation rate from the average interseismic coupling over the last ~ 15–20 years (Figure 3), demonstrating that SSEs play a major role in the accommodation of plate motion (Wallace and Beavan, 2010).

The fact that the campaign and continuous GPS data reveal very different subduction interface slip behavior at north vs. south Hikurangi makes it an ideal locale to investigate the physical controls on subduction megathrust slip. The high rates of contemporary elastic strain accumulation (and deeper slow slip) in the south suggest that southern Hikurangi may be more prone to rupture in a great (M_W > 8.0) megathrust earthquake than the aseismic creep/slow slip event dominated northern part of the margin. However, we certainly cannot rule out seismogenic rupture at North Hikurangi as well.

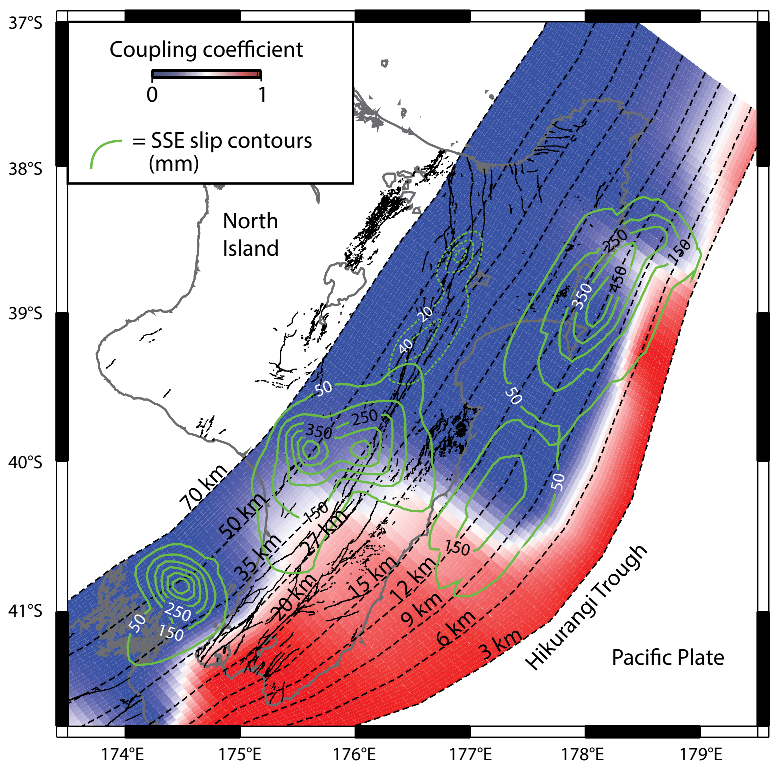


Figure 3. Interseismic coupling coefficients (see red to blue scale) from campaign GPS measurements (Wallace et al., 2012a) and cumulative slip in slow-slip events (SSEs) from 2002–2012 (green contours, labeled in mm; from Wallace et al., 2012b). Dashed green contours show slip in a deep central Hikurangi SSE in 2008 (Wallace and Eberhart-Phillips, 2013). Dashed black contours showing the depth to the subduction interface (in km below sea level) are from Ansell and Bannister (1996), and thus present an earlier version of the interface geometry compared to the more recent one shown in Figure 1 from Williams et al. (2014).

SEISMIC AND TSUNAMI POTENTIAL AT HIKURANGI AND ITS IMPLICATIONS

To conduct an integrated assessment of Hikurangi subduction interface seismic and tsunami potential, we evaluate the GPS coupling and slow slip results in tandem with the paleoseismological and paleotsunami results to develop a plausible worst-case rupture scenario. The synchroneity of sudden subsidence events along the Hikurangi margin

(Figure 2) indicates a whole-margin rupture is possible. If we assume that likely subduction interface rupture scenarios include the southern, deeply locked portion along with rupture of the shallow SSE source area at the central and northern Hikurangi margin, we obtain vertical tectonic deformation results (Figure 4) that are compatible with observations of subsidence in the northern South Island and along the southern and northern Hawke's Bay coastline and also compatible with uplift along the Wairarapa coast as evidenced by marine terraces there (Figure 2). Combined, the paleoseismological and GPS results suggest a deeper down-dip limit of slip in megathrust earthquakes at southern Hikurangi (~ 30 km depth) and a shallower down-dip limit (~ 15 km depth) at northern and central Hikurangi. The exception to the good paleoseismic/GPS correlation is the observation of coastal uplift events at Mahia Peninsula and at Pakarae (Sites 7 and 8 in Figure 4). However, coastal uplift at these locations is thought to be due to slip on splay faults; for example, the Lachlan Fault uplifts the Mahia Peninsula (Barnes et al., 2002) and the Gable End Fault uplifts the Pakarae area (Mountjoy and Barnes, 2011). These faults may slip simultaneously with the subduction interface.

In Figure 5, we show results from tsunami models due to the whole margin rupture scenario from Figure 4, adapted from Power et al. (2008) and Fraser et al. (2014). Such an event would inundate much of the east coast of North Island, with predicted water levels in excess of 10 m above sea level at many locations along the coastline. We note that a feature of the whole-margin scenario shown in Figures 4 and 5 is the use of the geodetic coupling model to produce a plausible distributed slip scenario (Figure 4). Strong similarities between geodetic locking distributions and coseismic slip in recent major megathrust earthquakes (Miura et al., 2004; Chlieh et al., 2008; Moreno et al., 2010; Loveless and Meade, 2011; Protti et al., 2014) justify the use of geodetic coupling models to help inform Hikurangi margin tsunami generation models. However, the details of slip in any future Hikurangi subduction earthquake events are highly uncertain, and a suite of alternative models should also be considered, preferably via a probabilistic approach, including rupture of areas that are currently aseismically creeping (e.g., Power, 2013). Detailed tsunami

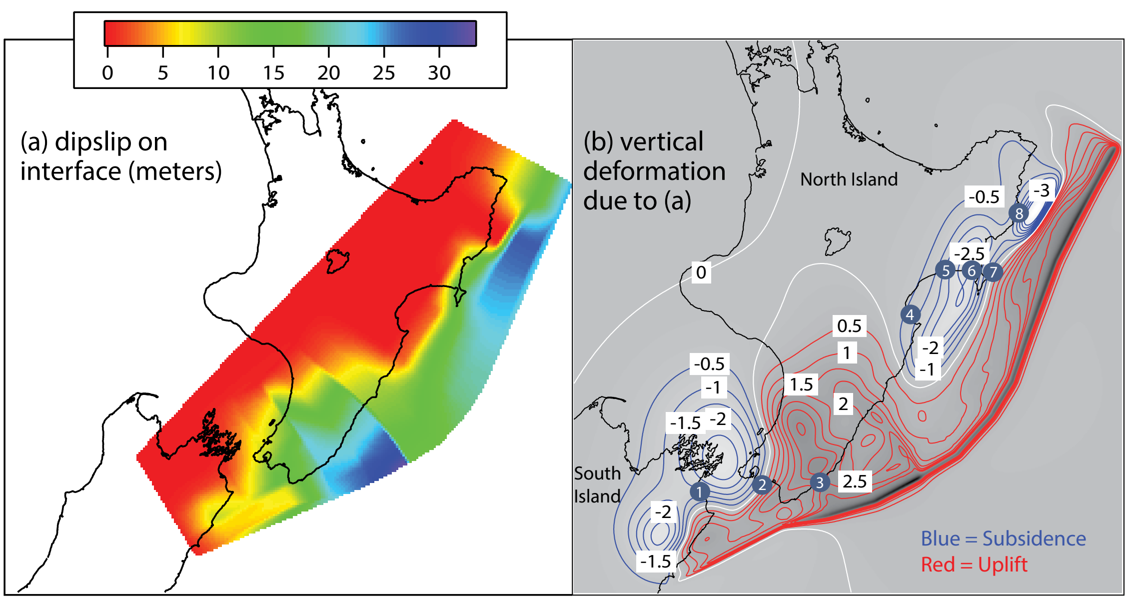


Figure 4. (a) A hypothetical scenario of rupture of the entire Hikurangi margin including the interseismically coupled area and SSE source areas offshore northern and central Hikurangi (Figure 3). (b) Predicted vertical deformation in this scenario (contour intervals are 0.5 m, labeled in m). Blue indicates areas of predicted subsidence, and red shows areas of uplift. The slip amounts used in the interseismically coupled area assume reversal of 800 years of accumulated slip deficit (using interseismic slip deficit rates from Wallace et al., 2012a; e.g., Figure 3), while the slip amounts within the SSE source area are tuned to produce vertical deformation consistent with that observed in Hawkes Bay paleoseismic studies (see Paleoearthquake and Paleotsunami Studies section in the text). Note that the use of 800 years of slip deficit does not imply an 800-year recurrence for such events, but rather provides a convenient way to assist with generation of distributed slip models. Numbers in blue circles correspond to paleoseismic sites in Figure 2. This slip scenario is also used to inform tsunami models that assume whole margin rupture in Figure 5 (see also Fraser et al., 2014).

inundation modeling is also required to accurately determine runup heights, which could be approximately double that of the water level heights shown in Figure 5. For example, results of tsunami-inundation modeling demonstrated significant inundation of Napier (by up to 7 km) and Gisborne due to the whole margin scenarios, underscoring the importance of understanding the threat posed by such events (Wang et al., 2009; Fraser et al., 2014).

It is important to note that to fit coseismic subsidence observed in the Hawkes Bay region (Figure 2) requires significant slip within the source area of repeated slow slip events beneath Hawke Bay (Cochran et al., 2006; Wallace and Beavan, 2010; Wallace and Eberhart-Phillips, 2013; Figures 3 and 4). Observations and numerical modeling suggest that slow slip events occur within a conditionally stable frictional regime at the boundary between velocity weakening (seismic) and velocity strengthening (aseismic) behavior (Liu and Rice, 2005; Schwartz and Rokosky, 2007). If subsidence at Ahuriri Lagoon (Figure 2) is due to slip on the plate interface within the slow slip source area, the conditionally stable portion of the Hikurangi subduction interface can also undergo large seismic slip, and is not restricted only to episodic slow slip behavior that we observe at present. If slow slip regions can also rupture with large seismic slip (as we suggest here), this has important implications for the estimation of seismic hazard at subduction margins elsewhere. For example, in Cascadia, there is significant debate about whether or not the slow slip region slips during megathrust earthquakes, which is of utmost importance for anticipating the level of seismic shaking that might occur at Seattle and other urban areas in the Pacific Northwest.

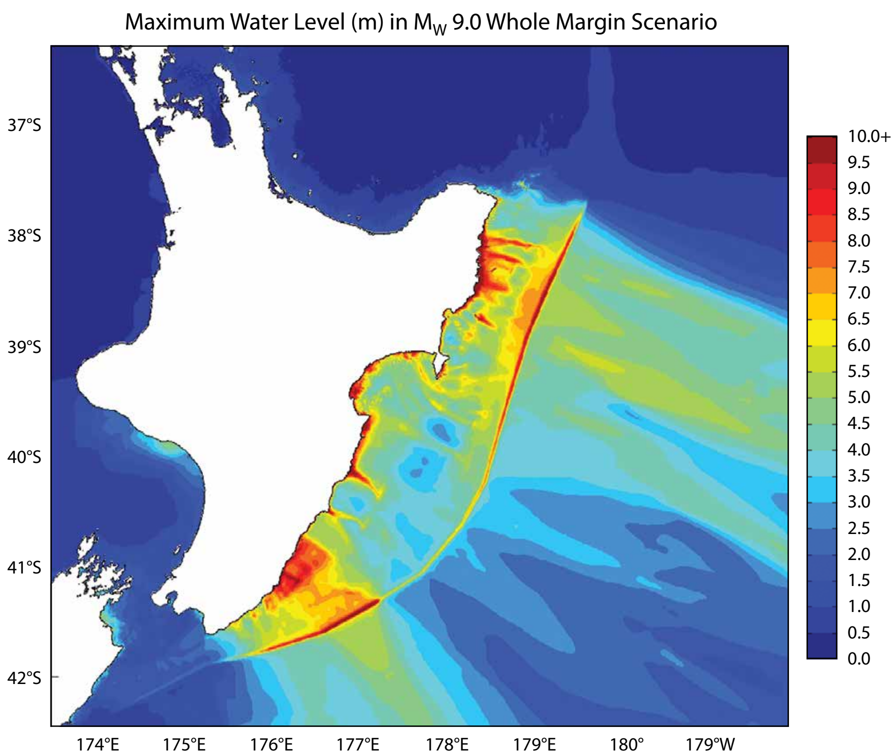


Figure 5. Estimated maximum tsunami water levels, relative to background, following an M_W 9.0 whole-margin plate interface earthquake scenario. The vertical deformation model used is the same as the one shown in Figure 4 and in the whole margin scenario in Fraser et al. (2014). Runup heights could be approximately double that of the water levels shown at the coast, but accurate estimates of onshore tsunami heights require finer scale modeling. Calculation was performed with the COMCOT model (Wang and Liu, 2006).

COMPARISON BETWEEN THE HIKURANGI SUBDUCTION MARGIN AND THE JAPAN TRENCH: IMPLICATIONS FOR SEISMIC AND TSUNAMI POTENTIAL AT HIKURANGI

There are many striking similarities between the Hikurangi margin and the Japan Trench: (1) both are characterized by subduction of Cretaceous oceanic crust (Finn et al., 1994; Mortimer and Parkinson, 1996), (2) large portions of the interface at both subduction margins are interseismically coupled between earthquakes (Nishimura et al., 2004; Suwa et al., 2006; Hashimoto, et al., 2009; Wallace et al., 2004, 2012a), and (3) the Japan Trench and the northern Hikurangi margin are each thought to be the site of subduction erosion (von Huene and Lallemand, 1990; Collot et al., 1996, 2001). These similarities raise an important, unresolved question of whether or not the Hikurangi subduction thrust can produce great (M_W 9.0 or larger) earthquakes (Figure 4) similar to the one that occurred at the Japan Trench in March 2011. One way to approach this question is to compare the interseismic coupling distribution at the Japan Trench prior to the 2011 earthquake with that at Hikurangi (Figure 6).

Numerous studies show that the subduction interface offshore Northeast Honshu that slipped in the March 2011 M_W 9.0 earthquake was interseismically coupled and accumulating elastic strain prior to the earthquake (Mazzotti et al., 2000; Nishimura et al., 2004; Suwa et al., 2006; Hashimoto et al., 2009; Wallace et al., 2009b; Figure 6). To evaluate whether an M_W 9.0 scenario similar to the 2011 Tōhoku-Oki earthquake is plausible at the Hikurangi margin, we compare the interseismic coupling distributions of the two margins; for consistency, we show coupling models that use identical elastic block modeling approaches (Figure 6). We superimpose the slip distribution for the 2011 M_W 9.0 earthquake on both coupling maps to show that much of the region of the Japan Trench that was interseismically coupled prior to the 2011 earthquake ruptured coseismically, and also to demonstrate that the dimensions of the strongly locked and SSE source areas of the Hikurangi margin are comparable to the interseismically locked and 2011 M_W 9.0 coseismic slip regions. The dimensions of the Japan Trench subduction interface that ruptured in the 2011 M_W 9.0 earthquake is similar in size to the large, southern Hikurangi coupled patch plus the slow slip region in the Hawke's Bay and Gisborne region (Figures 4 and 6), making a similar M_W 9.0 scenario at Hikurangi seem plausible. We suggest that the 1,000–1,500 year recurrence of large subsidence events observed along the Hawke Bay coastline, and some temporally correlated uplift events further south (Figure 2), could in fact represent whole margin rupture of the Hikurangi megathrust. Further paleoseismic and paleotsunami investigations on North Island are required to test this idea.

We note that the Wallace et al. (2009b) interseismic coupling model and the Mazzotti et al. (2000) coupling model were the only Japan Trench coupling models published prior to the 2011 earthquake that assumed interseismic coupling could occur all the way to the trench. Other interseismic coupling studies published prior to 2011 assumed steady aseismic creep at the Japan Trench (Nishimura et al., 2004; Suwa et al., 2006; Hashimoto et al., 2009; Loveless and Meade, 2010). The reason for the different models (locking at the trench vs. no locking at the trench) is that the degree of interseismic coupling on the shallow subduction interface located > 50 km offshore Northeast Japan is simply not resolvable with shore-based GPS methods. However, in light of the very large and unexpected coseismic slip observed near the Japan Trench (> 50 m) during the 2011 M_W 9.0 earthquake (Fujiwara et al., 2011; Ito et al., 2011),

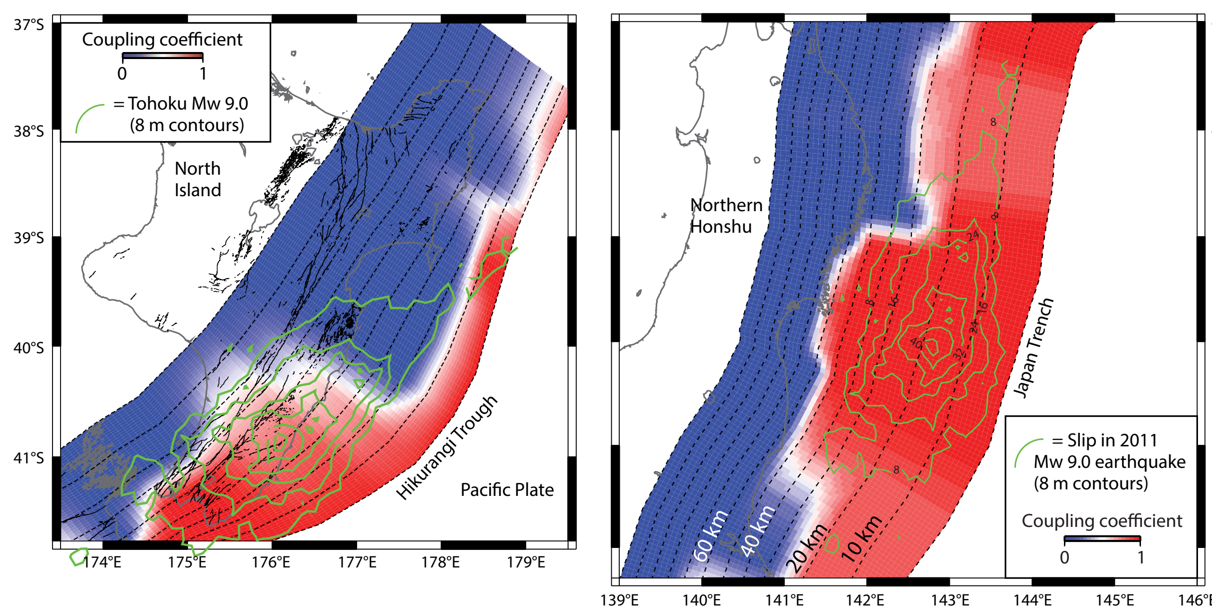


Figure 6. Comparison of interseismic coupling at the Hikurangi margin (left, Wallace et al., 2012a) and the Japan Trench offshore northern Honshu determined prior to the 2011 M_W 9.0 earthquake (right, Wallace et al., 2009b) plotted at the same scale. Green contours on both are the coseismic slip distribution on the Japan Trench during the 2011 M_W 9.0 earthquake from GPS (Simons et al., 2011), and the yellow star shows the earthquake's epicenter. Coseismic slip distribution on the Hikurangi subduction interface is superimposed to demonstrate that a region ruptured in the M_W 9.0 2011 Tōhoku earthquake is similar in dimensions to the locked portion + the shallow SSE source area at Hikurangi. The slip distribution in the 2011 earthquake from Simons et al. (2011) is based only on shore-based cGPS (continuously operating GPS) measurements; other studies that utilize offshore data demonstrate large (> 50 m) coseismic slip near the trench (not shown here; Sato et al., 2011; Fujiwara et al., 2011).

and the strong contribution of this shallow slip to the tsunami generation (Koketsu et al., 2011), it seems prudent to assume that interseismic locking to the trench (Figure 6) and large near-trench slip is possible at any subduction zone, unless proven otherwise. Seafloor geodetic studies at the Peru-Chile Trench also show clear evidence for interseismic coupling all the way to the trench (Gagnon et al., 2005). However, if the large near-trench slip in the 2011 M_W 9.0 earthquake is due to dynamic overshoot (Ide et al., 2011) rather than the reversal of previously accumulated elastic strain, then interseismic coupling at the trench may not be required to produce large near-trench coseismic slip.

> "ALTHOUGH MAJOR ADVANCES HAVE BEEN MADE IN OUR UNDERSTANDING OF THE HIKURANGI MEGATHRUST OVER THE LAST 10 YEARS, WE ARE CLEARLY IN THE EARLY STAGES OF UNDERSTANDING THE THREAT THAT THE HIKURANGI SUBDUCTION THRUST POSES TO THE NEW ZEALAND REGION."

FUTURE DIRECTIONS

Although major advances have been made in our understanding of the Hikurangi megathrust over the last 10 years, we are clearly in the early stages of understanding the threat that the Hikurangi subduction thrust poses to the New Zealand region. Improving the paleoseismic record for the Hikurangi margin is of utmost importance if we are to discern the magnitude, frequency, and locations of past Hikurangi subduction thrust earthquakes and associated tsunamis. To accomplish this, more detailed margin-wide studies of uplift, subsidence, and tsunami deposits are required, complemented by offshore work on marine turbidites, which may hold a promising record of subduction thrust events (e.g., Pouderoux et al., 2014). In particular, high-resolution paleoecological reconstruction and radiocarbon dating is needed so that deformation events and paleotsunamis can be identified and dated to the smallest possible uncertainty range and more rigorous tests of margin-wide correlations can be made. Unraveling the paleoseismic history of nearshore faults (e.g., Pondard and Barnes, 2010) will also help to establish which coastal sites are recording local upper plate deformation and which are recording plate interface deformation, or if some sites record a mixture of both tectonic signals.

Continued GPS monitoring is also needed to evaluate how megathrust slip behavior evolves throughout a seismic cycle, and also to refine estimates of interseismic coupling and slow slip. Seafloor geodetic studies, such as absolute pressure sensors to measure vertical deformation of the seafloor in slow slip events (or earthquakes) (e.g., Ito et al., 2013) and GPS-acoustic techniques to measure horizontal deformation of the seafloor (e.g., Gagnon et al., 2005), are needed to determine the slip behavior of the Hikurangi megathrust near the trench.

A question that has major implications for assessing subduction thrust seismic and tsunami hazards worldwide is whether or not areas that appear to be undergoing episodic slow-slip events and/or aseismic creep can also rupture seismically with large slip. Slow slip events at the northern Hikurangi margin are among the shallowest well-documented SSEs on Earth. Over the last few years, a series of proposals have been submitted to the International Ocean Discovery Program (IODP) to drill into the source and surrounding areas of episodic slow slip events at the northern Hikurangi margin (Saffer et al., 2011; Wallace et al., 2013). Evidence of past rapid (e.g., seismic) slip may be detected from samples of fault slip zones obtained in the drillcore by looking for indicators of frictional heating such as frictional melt (pseudotachylite), changes in clay mineralogy, and thermal maturation of organic matter (Magloughlin and Spray, 1992; Polissar et al., 2011; Sakaguchi et al., 2011). If we do find evidence for large seismic slip in the SSE source area, this will add further credence to the suggestion that the Hikurangi margin could rupture in M_W 9.0 earthquakes.

Future work on probabilistic tsunami hazard assessment will need to address the potentially highly variable megathrust slip behavior along the length of the Hikurangi subduction margin, such as variations in coupling and convergence rates as revealed by geodesy and paleoseismic evidence for megathrust earthquakes. We must also develop models that account for the currently untestable possibility that geodetic locking and slow slip locations are not persistent in time. Modeling the collective effects of multiple, and often interacting, megathrust slip behaviors along the margin will likely require techniques for generating synthetic events according to probability distributions defined from geophysical measurements. Closely related to this is the role of nonuniform slip in tsunami generation (Geist, 2002), revealed to be influential on the distribution of tsunami impacts in recent events such as the 2011 Tōhoku tsunami. Methods for incorporating the effects of spatially distributed slip variations need to be considered for tsunami hazard modeling. Future hazard models will also need to be refined using paleotsunami and paleoearthquake records for the margin.

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REFERENCES

Ansell, J., and S. Bannister. 1996. Shallow morphology of the subducted Pacific Plate along the Hikurangi margin, New Zealand. *Physics of the Earth and Planetary Interiors* 93:3–20, http://dx.doi.org/10.1016/0031-9201(95)03085-9.

Barnes, P.M., A. Nicol, and T. Harrison. 2002. Late Cenozoic evolution and earthquake potential of an active listric thrust complex above the Hikurangi subduction zone, New Zealand. *Geological Society of America Bulletin* 114:1,379–1,405, http://dx.doi.org/10.1130/0016-7606(2002)114<1379:LCEAEP>2.0.CO;2.

Beavan, R.J., and D.J. Darby. 2005. Fault slip in the 1855 Wairarapa earthquake based on new and reassessed vertical motion observations: Did slip occur on the subduction interface? Pp. 31–41 in *The 1855 Wairarapa Earthquake Symposium: 150 Years of Thinking About Magnitude 8+ Earthquakes and Seismic Hazard in New Zealand*. September 8–10, 2005, Proceedings Volume, Greater Wellington Regional Council, Wellington.

Bell, R., R. Sutherland, D.H.N. Barker, S. Henrys, S. Bannister, L. Wallace, and J. Beavan. 2010. Seismic reflection character of the Hikurangi subduction interface, New Zealand, in the region of repeated Gisborne slow slip events. *Geophysical Journal International* 180:34–48, http://dx.doi.org/10.1111/j.1365-246X.2009.04401.x.

Berryman, K.R. 1993. Age, height, and deformation of Holocene marine terraces at Mahia Peninsula, Hikurangi subduction margin, New Zealand. *Tectonics* 12:1,347–1,364, http://dx.doi.org/10.1029/93TC01542.

Berryman, K., Y. Ota, T. Miyauchi, A. Hull, K. Clark, K.I. Ishibashi, Nozomi, and N. Litchfield. 2011. Holocene paleoseismic history of upper-plate faults in the southern Hikurangi Margin, New Zealand, deduced from marine terrace records. *Bulletin of the Seismological Society of America* 101:2,064–2,087, http://dx.doi.org/10.1785/0120100282.

Chlieh, M., J.P. Avouac, K. Sieh, D.H. Natawidjaja, and J. Galetzka. 2008. Heterogeneous coupling of the Sumatran megathrust constrained by geodetic and paleogeodetic measurements. *Journal of Geophysical Research* 113, B05305, http://dx.doi.org/10.1029/2007JB004981.

Cisternas, M., B.F. Atwater, F. Torrejón, Y. Sawai, G. Machuca, M. Lagos, A. Eipert, C. Youlton, I. Salgado, T. Kamataki, and others. 2005. Predecessors of the giant 1960 Chile earthquake. *Nature* 437:404–407, http://dx.doi.org/10.1038/nature03943.

Clague, J.J. 1997. Evidence for large earthquakes at the Cascadia subduction zone. *Reviews of Geophysics* 35:439–460, http://dx.doi.org/10.1029/97RG00222.

Clark, K.J., B.W. Hayward, U.A. Cochran, H.R. Grenfell, E. Hemphill-Haley, D.C. Mildenhall, M.A. Hemphill-Haley, and L.M. Wallace. 2011. Investigating subduction earthquake geology along the southern Hikurangi margin using palaeoenvironmental histories of intertidal inlets. *New Zealand Journal of Geology and Geophysics* 54(3):255–271, http://dx.doi.org/10.1080/00288306.2011.562903.

Cochran, U.A., K.R. Berryman, J. Zachariasen, D.C. Mildenhall, B.W. Hayward, K. Southall, C.J. Hollis, P. Barker, L.M. Wallace, B. Alloway, and K. Wilson. 2006. Paleoecological insights into subduction zone earthquake occurrence, eastern North Island, New Zealand. *Geological Society of America Bulletin* 118:1,051–1,074, http://dx.doi.org/10.1130/B25761.1.

Collot, J.-Y., J. Delteil, K.B. Lewis, B. Davy, G. Lamarche, J.-C. Audru, P. Barnes, F. Chanier, E. Chaumillon, S. Lallemand, and others. 1996. From oblique subduction to intra-continental transpression: Structures of the southern Kermadec-Hikurangi margin from multibeam bathymetry, side-scan sonar and seismic reflection. *Marine Geophysical Researches* 18:357–381, http://dx.doi.org/10.1007/BF00286085.

Collot, J.-Y., K. Lewis, G. Lamarche, and S. Lallemand. 2001. The giant Ruatoria debris avalanche on the northern Hikurangi margin, New Zealand: Result of oblique seamount subduction. *Journal of Geophysical Research* 106(B9):19,271–19,297, http://dx.doi.org/10.1029/2001JB900004.

Darby, D., and J. Beavan. 2001. Evidence from GPS measurements for contemporary interplate coupling on the southern Hikurangi subduction thrust and for partitioning of strain in the upper plate. *Journal of Geophysical Research* 106:30,881–30,891, http://dx.doi.org/10.1029/2000JB000023.

Doser, D.I., and T.H. Webb. 2003. Source parameters of large historical (1917–1961) earthquakes, North Island, New Zealand. *Geophysical Journal International* 152:795–832, http://dx.doi.org/10.1046/j.1365-246X.2003.01895.x.

Douglas, A., J. Beavan, L. Wallace, and J. Townend. 2005. Slow slip on the northern Hikurangi subduction interface, New Zealand. *Geophysical Research Letters* 32, L16305, http://dx.doi.org/10.1029/2005GL023607.

Downes, G., T.H. Webb, M.J. McSaveney, C. Chague-Goff, D.J. Darby, and A. Barnett. 2000. The March 25 and May 17 1947 Gisborne earthquakes and tsunami: Implication for tsunami hazard for East Coast, North Island, New Zealand. Pp. 55–67 in *Tsunami Risk Assessment Beyond 2000: Theory, Practice and Plans*. Proceedings of Joint IOC–IUGG International Workshop, V.K. Gusiakov, B.W. Levin, and O.I. Yakovenko, eds, Moscow.

Dragert, H., K. Wang, and T. James. 2001. A silent slip event on the deeper Cascadia subduction interface. *Science* 292:1,525–1,528, http://dx.doi.org/10.1126/science.1060152.

Finn, C., G. Kimura, and K. Suyehiro. 1994. Introduction to the special section Northeast Japan: A case history of subduction. *Journal of Geophysical Research* 99(B11):22,137–22,145, http://dx.doi.org/10.1029/94JB01130.

Fraser, S.A., W.L. Power, X. Wang, L.M. Wallace, C. Mueller, and D.M. Johnston. 2014. Tsunami inundation in Napier, New Zealand, due to local earthquake sources. *Natural Hazards* 70:415–445, http://dx.doi.org/10.1007/s11069-013-0820-x.

Fujiwara, T., S. Kodaira, T. No, Y. Kaiho, N. Takahashi, and Y. Kaneda. 2011. The 2011 Tohoku-Oki earthquake: Displacement reaching the trench axis. *Science* 334:1,240.

Gagnon, K., C.D. Chadwell, and E. Norabuena. 2005. Measuring the onset of locking in the Peru–Chile Trench with GPS and acoustic measurements. *Nature* 434:205–208, http://dx.doi.org/10.1038/nature03412.

Geist, E.L. 2002. Complex earthquake rupture and local tsunamis. *Journal of Geophysical Research* 107(B5), http://dx.doi.org/10.1029/2000JB000139.

Grapes, R., and G. Downes. 1997. The 1855 Wairarapa, New Zealand, earthquake: Analysis of historical data. *Bulletin of the New Zealand National Society for Earthquake Engineering* 30(4):271–368.

Hashimoto, C., A. Noda, T. Sagiya, and M. Matsu'ura. 2009. Interplate seismogenic zones along the Kuril–Japan Trench inferred from GPS data inversion. *Nature Geoscience* 2:141–144, http://dx.doi.org/10.1038/ngeo421.

Hayward, B.W., H.R. Grenfell, A.T. Sabaa, R. Carter, U.A. Cochran, J.H. Lipps, P.R. Shane, and M.S. Morley. 2006. Micropaleontological evidence of large earthquakes in the past 7200 years in southern Hawke's Bay, New Zealand. *Quaternary Science Reviews* 25:1,186–1,207, http://dx.doi.org/10.1016/j.quascirev.2005.10.013.

Hayward, B.W., K.J. Wilson, M. Morley, U. Cochran, H.R. Grenfell, A. Sabaa, and R. Daymond-King. 2010. Microfossil record of the Holocene evolution of coastal wetlands in a tectonically active region of New Zealand. *The Holocene* 30:405–421, http://dx.doi.org/10.1177/0959683609353431.

Henrys, S., A.Wech, R. Sutherland, T. Stern, M. Savage, H. Sato, K. Mochizuki, T. Iwasaki, D. Okaya, A. Seward, and others. 2013. SAHKE geophysical transect reveals crustal and subduction zone structure at the southern Hikurangi margin. *Geochemistry, Geophysics, Geosystems* 14:2,063–2,083, http://dx.doi.org/10.1002/ggge.20136.

Ide, S., A. Baltay, and G. Beroza. 2011. Shallow dynamic overshoot and energetic deep rupture in the 2011 M_W 9.0 Tohoku-Oki earthquake. *Science* 332:1,426–1,429.

Ito, Y., R. Hino, M. Kido, H. Fujimoto, Y. Osada, D. Inazu, Y. Ohta, T. Iinuma, M. Ohzono, S. Miura, and others. 2013. Episodic slow slip events in the Japan subduction zone before the 2011 Tohoku-Oki earthquake. *Tectonophysics* 600:14–26, http://dx.doi.org/10.1016/j.tecto.2012.08.022.

Ito, Y., T. Tsuji, Y. Osada, M. Kido, D. Inazu, Y. Hayashi, H. Tsushima, R. Hino, and H. Fujimoto. 2011. Frontal wedge deformation near the source region of the 2011 Tohoku-Oki earthquake. *Geophysical Research Letters* 38, L00G05, http://dx.doi.org/10.1029/2011GL048355.

Kanamori, H. 1972. Mechanism of tsunami earthquakes. *Physics of the Earth and Planetary Interiors* 6:346–359, http://dx.doi.org/10.1016/0031-9201(72)90058-1.

King, D.N.T., J. Goff, and A. Skipper. 2007. Māori environmental knowledge and natural hazards in Aotearoa-New Zealand. *Journal of the Royal Society of New Zealand* 37:59–73, http://dx.doi.org/10.1080/03014220709510536.

Koketsu, K., Y. Yokota, N. Nishimura, Y. Yagi, S. Miyazaki, K. Statake, Y. Fujii, H. Miyake, S. Sakai, Y. Yamanaka, and T. Okada. 2011. A unified source model for the 2011 Tohoku earthquake. *Earth and Planetary Science Letters* 310:480-487, http://dx.doi.org/10.1016/j.epsl.2011.09.009.

Liu, Y., and J.R. Rice. 2005. Aseismic slip transients emerge spontaneously in three dimensional rate and state modeling of subduction earthquake sequences. *Journal of Geophysical Research* 110, B08307, http://dx.doi.org/10.1029/2004JB003424.

Loveless, J.P., and B.J. Meade. 2010. Geodetic imaging of plate motions, slip rates, and partitioning of deformation in Japan. *Journal of Geophysical Research* 115, B02410, http://dx.doi.org/10.1029/2008JB006248.

Loveless, J.P., and B.J. Meade. 2011. Spatial correlation of interseismic coupling and coseismic rupture extent of the 2011 M_W = 9.0 Tohoku-Oki earthquake. *Geophysical Research Letters* 38, L17306, http://dx.doi.org/10.1029/2011GL048561.

Magloughlin, J.F., and J.G. Spray. 1992. Frictional melting processes and products in geological materials: introduction and discussion. *Tectonophysics* 204:197–204, http://dx.doi.org/10.1016/0040-1951(92)90307-R.

Mazzotti, S., X. Le Pichon, P. Henry, and S. Miyazaki. 2000. Full interseismic locking of the Nankai and Japan-west Kurile subduction zones: An analysis of uniform elastic strain accumulation in Japan constrained by permanent GPS. *Journal of Geophysical Research* 105(B6):13,159–13,177, http://dx.doi.org/10.1029/2000JB900060.

McCaffrey, R. 2008. Global frequency of magnitude 9 earthquakes. *Geology* 36(3):263–266, http://dx.doi.org/10.1130/G24402A.1.

McFadgen, B.G. 2008. *Hostile Shores: Catastrophic Events in Prehistoric New Zealand and Their Impact on Maori Coastal Communities.* Auckland University Press.

McSaveney, M.J., I.J. Graham, J.G. Begg, A.G. Beu, A.G. Hull, K. Kim, and A. Zondervan. 2006. Late Holocene uplift of beach ridges at Turakirae Head, south Wellington coast, New Zealand. *New Zealand Journal of Geology and Geophysics* 49:337–358, http://dx.doi.org/10.1080/00288306.2006.9515172.

Miura, S., Y. Suwa, A. Hasegawa, and T. Nishimura. 2004. The 2003 M8.0 Tokachi-Oki earthquake: How much has the great event paid back slip debts? *Geophysical Research Letters* 31, L05613, http://dx.doi.org/10.1029/2003GL019021.

Moreno, M., M. Rosenau, and O. Oncken. 2010. 2010 Maule earthquake slip correlates with preseismic locking of Andean subduction zone. *Nature* 467:198–202, http://dx.doi.org/10.1038/nature09349.

Mortimer, N., and D. Parkinson. 1996. Hikurangi Plateau: A Cretaceous large igneous province in the southwest Pacific Ocean. *Journal Geophysical Research* 101(B1):687–696, http://dx.doi.org/10.1029/95JB03037.

Mountjoy, J.J., and P.M. Barnes. 2011. Active upper plate thrust faulting in regions of low plate interface coupling, repeated slow slip events, and coastal uplift: Example from the Hikurangi Margin, New Zealand. *Geochemistry, Geophysics, Geosystems* 12, Q01005, http://dx.doi.org/10.1029/2010GC003326.

Nishimura, T., T. Hirasawa, S. Miyazaki, T. Sagiya, T. Tada, S. Miura, and K. Tanaka. 2004. Temporal change of interplate coupling in northeastern japan during 1995–2002 estimated from continuous GPS observations. *Geophysical Journal International* 157:901–916, http://dx.doi.org/10.1111/j.1365-246X.2004.02159.x.

Polissar, P.J., H.M. Savage, and E.E. Brodsky. 2011. Extractable organic material in fault zones as a tool to investigate frictional stress. *Earth and Planetary Science Letters* 311:439–447, http://dx.doi.org/10.1016/j.epsl.2011.09.004.

Pondard, N., and P.M. Barnes. 2010. Structure and paleoearthquake records of active submarine faults, Cook Strait, New Zealand: Implications for fault interactions, stress loading, and seismic hazard. *Journal Geophysical Research* 115, B12320, http://dx.doi.org/10.1029/2010JB007781.

Power, W.L. (compiler). 2013. *Review of Tsunami Hazard in New Zealand (2013 Update).* GNS Science Consultancy Report 2013/131, 222 pp.

Power, W., and E. Tolkova. 2013. Forecasting tsunamis in Poverty Bay, New Zealand, with deep-ocean gauges. *Ocean Dynamics* 63:1,213–1,232, http://dx.doi.org/10.1007/s10236-013-0665-6.

Power, W.L., L. Wallace, and M. Reyners. 2008. *Tsunami Hazard Posed by Earthquakes on the Hikurangi Subduction Zone Interface.* GNS Science Consultancy Report 2008/40. http://www.eqc.govt.nz/sites/public_files/1600-tsunami-hazard-Hikurangi-subduction-zone-interface.pdf.

Pouderoux, H., J.-N. Proust, and G. Lamarche. 2014. Submarine paleoseismology of the northern Hikurnagi subduction margin of New Zealand as deduced form Turbidite records since 16 ka. *Quaternary Science Reviews* 84:116–131, http://dx.doi.org/10.1016/j.quascirev.2013.11.015.

Protti, M., V. González, A.V. Newman, T.H. Dixson, S.Y. Schwartz, J.S. Marshall, L. Feng. J.I., Walter, R. Maiservisi, and S.E. Owen. 2014. Nicoya earthquake rupture anticipated by geodetic measurement of the locked plate interface. *Nature Geoscience* 7:117–121, http://dx.doi.org/10.1038/ngeo2038.

Saffer, D., P. Barnes, L. Wallace, S. Henrys, M. Underwood, M. Torres, and the Hikurangi Margin Working Group. 2011. Unlocking the secrets of slow slip by drilling at the northern Hikurangi subduction margin, New Zealand:

Riserless drilling to sample and monitor the forearc and subduction plate. IODP proposal 781A-Full, http://www.iodp.org/700.

Sakaguchi, A., F. Chester, D. Curewitz, O. Fabbri, D. Goldsby, G. Gaku, C.-F. Li, Y. Masaki, E.J. Screaton, A. Tsutsumi, and others. 2011. Seismic slip propagation to the updip end of plate boundary subduction interface faults: Vitrinite reflectance geothermometry on Integrated Ocean Drilling Program NanTroSEIZE cores. *Geology* 39:395–398, http://dx.doi.org/10.1130/G31642.1.

Satake, K., and B.F. Atwater. 2007. Long-term perspectives on Giant earthquakes and tsunamis at subduction zones. *Annual Review of Earth and Planetary Sciences* 35:349–374, http://dx.doi.org/10.1146/annurev.earth.35.031306.140302.

Sato, M., T. Ishikawa, N. Ujihara, S. Yoshida, M. Fujita, M. Mochizuki, and A. Asada. 2011. Displacement above the hypocenter of the 2011 Tohoku-Oki earthquake. *Science* 332:1,395, http://dx.doi.org/10.1126/science.1207401.

Sawai, Y., and H. Nasu. 2005. A 4500-year record of emergence events at Onnetoh, Hokkaido, northern Japan, reconstructed using plant macrofossils. *Marine Geology* 217(1):49–65, http://dx.doi.org/10.1016/j.margeo.2005.02.006.

Schwartz, S.Y. and J.M. Rokosky. 2007. Slow slip events and seismic tremor at circum-Pacific subduction zones. *Reviews of Geophysics* 45, RG3004, http://dx.doi.org/10.1029/2006RG000208.

Shennan, I., and S. Hamilton. 2006. Coseismic and pre-seismic subsidence associated with great earthquakes in Alaska. *Quaternary Science Reviews* 25:1–8, http://dx.doi.org/10.1016/j.quascirev.2005.09.002.

Simons, M., S.E. Minson, A. Sladen, F. Ortega, J. Jiang, S.E. Owen, L. Meng, J.-P. Ampuero, S. Wei, R. Chu, and others. 2011. The 2011 magnitude 9.0 Tohoku-Oki earthquake: Mosaicking the megathrust from seconds to centuries. *Science* 332: 1,421–1,425, http://dx.doi.org/10.1126/science.1206731.

Suwa, Y., S. Miura, A. Hasegawa, T. Sato, and K. Tachibana. 2006. Interplate coupling beneath NE Japan inferred from three-dimensional displacement field. *Journal of Geophysical Research* 111, B04402, http://dx.doi.org/10.1029/2004JB003203.

von Huene, R., and S. Lallemand. 1990. Tectonic erosion along the Japan and Peru convergent margins. *Geological Society of America Bulletin* 102:704–720, http://dx.doi.org/10.1130/0016-7606(1990)102<0704:TEATJA>2.3.CO;2.

Wallace, L.M., P. Barnes, R.J. Beavan, R.J. Van Dissen, N.J. Litchfield, J. Mountjoy, R.M. Langridge, G. Lamarche, and N. Pondard. 2012a. The kinematics of a transition from subduction to strike-slip: An example from the central New Zealand plate boundary. *Journal Geophysical Research* 117, B02405, http://dx.doi.org/10.1029/2011JB008640.

Wallace, L.M., and J. Beavan. 2010. Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand. *Journal of Geophysical Research* 115, B12402, http://dx.doi.org/10.1029/2010JB007717.

Wallace, L.M., J. Beavan, S. Bannister, and C. Williams. 2012b. Simultaneous long-term and short-term slow slip events at the Hikurangi subduction margin, New Zealand: Implications for processes that control slow slip event occurrence, duration, and migration. *Journal Geophysical Research* 117, B11402, http://dx.doi.org/10.1029/2012JB009489.

Wallace, L.M., J. Beavan, R. McCaffrey, and D. Darby. 2004. Subduction zone coupling and tectonic block rotations in the North Island, New Zealand. *Journal of Geophysical Research* 109, B12406, http://dx.doi.org/10.1029/2004JB003241.

Wallace, L.M., J. Beavan, S. Miura, and R. McCaffrey. 2009b. Using Global Positioning System data to assess tectonic hazards. Pp. 156–175 in *Volcanism, Tectonism and Siting of Nuclear Facilities*. C. Connor, L. Connor, and N. Chapman, eds, Cambridge University Press.

Wallace, L.M., and D. Eberhart-Phillips. 2013. Newly observed, deep slow slip events at the central Hikurangi margin, New Zealand: Implications for downdip variability of slow slip and tremor, and relationship to seismic structure. *Geophysical Research Letters* 40:5,393–5,398, http://dx.doi.org/10.1002/2013GL057682.

Wallace, L.M., M. Reyners, U. Cochran, S. Bannister, P.M. Barnes, K. Berryman, G. Downes, D. Eberhart-Phillips, A. Fagereng, S. Ellis, and others. 2009a. Characterizing the seismogenic zone of a major plate boundary subduction thrust: Hikurangi Margin, New Zealand. *Geochemistry, Geophysics, Geosystems* 10, Q10006, http://dx.doi.org/10.1029/2009GC002610.

Wallace, L.M., Y. Ito, S. Henrys, P. Barnes, D. Saffer, S. Kodaira, H. Tobin, M. Underwood, N. Bangs, A. Fagereng, and others. 2013. Unlocking the secrets of slow slip by drilling at the northern Hikurangi subduction margin, New Zealand: Riser drilling to intersect the plate interface. IODP proposal 781B-Full, http://www.iodp.org/700.

Wang, X., and P.L.F. Liu. 2006. An analysis of 2004 Sumatra earthquake fault plane mechanisms and Indian Ocean tsunami. *Journal of Hydraulic Research* 44:147–154, http://dx.doi.org/10.1080/00221686.2006.9521671.

Wang, X., G. Prasetya, W.L. Power, B. Lukovic, H. Brackley, and K.R. Berryman. 2009. *Gisborne District Council Tsunami Inundation Study*. GNS Science Consultancy Report, 233 pp., http://www.gdc.govt.nz/assets/Strategies/Wainui-Beach-Management/Tsunami-Inundation-Study-pgs-1-19.pdf.

Webb, T.H., and H. Anderson. 1998. Focal mechanisms of large earthquakes in the North island of New Zealand: Slip partitioning at an oblique active margin. *Geophysical Journal International* 134:40–86, http://dx.doi.org/10.1046/j.1365-246x.1998.00531.x.

Williams, C.A., D. Eberhart-Phillips, S. Bannister, D.H.N. Barker, S. Henrys, M. Reyners, and R. Sutherland. 2014. Revised interface geometry for the Hikurangi subduction zone, New Zealand. *Seismological Research Letters* 84:1,066–1,073, http://dx.doi.org/10.1785/0220130035.

Wilson, K., K. Berryman, N. Litchfield, and T. Little. 2006. A revision of mid-late Holocene marine terrace distribution and chronology at the Pakarae River mouth, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics* 49:477–489, http://dx.doi.org/10.1080/00288306.2006.9515182.