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Slow Slip Events in New Zealand

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Abstract

Continuously operating global positioning system sites in the North Island of New Zealand have revealed a diverse range of slow motion earthquakes on the Hikurangi subduction zone. These slow slip events (SSEs) exhibit diverse characteristics, from shallow (<15 km), short (<1 month), frequent (every 1–2 years) events in the northern part of the subduction zone to deep (>30 km), long (>1 year), less frequent (approximately every 5 years) SSEs in the southern part of the subduction zone. Hikurangi SSEs show intriguing relationships to interseismic coupling, seismicity, and tectonic tremor, and they exhibit a diversity of interactions with large, regional earthquakes. Due to the marked along-strike variations in Hikurangi SSE characteristics, which coincide with changes in physical characteristics of the subduction margin, the Hikurangi subduction zone presents a globally unique natural laboratory to resolve outstanding questions regarding the origin of episodic, slow fault slip behavior.

- New Zealand's Hikurangi subduction zone hosts slow slip events with a diverse range of depth, size, duration, and recurrence characteristics.
- Hikurangi slow slip events show intriguing relationships with seismicity ranging from small earthquakes and tremor to larger earthquakes.
- Slow slip events play a major role in the accommodation of plate motion at the Hikurangi subduction zone.
- Many aspects of the Hikurangi subduction zone make it an ideal natural laboratory to resolve the physical processes controlling slow slip.

1. INTRODUCTION

Movement between tectonic plates is largely accommodated on faults within the boundary zone between the plates. Until recently, scientists largely viewed fault slip as occurring in one of two ways: as sudden, seismic slip in an earthquake (centimeters to meters per second), or as steady creep at plate motion rates (centimeters per year). However, installation of continuously monitoring geodetic and seismic networks at plate boundaries around the world has revealed a far more complex picture, where movement between the plates can occur episodically but at a rate too slow to produce an earthquake (e.g., Dragert et al. 2001, Schwartz & Rokosky 2007). Such episodic, slow motion earthquakes, known as slow slip events (SSEs), can involve centimeters to tens of centimeters of fault movement over days to years. The realization that an unexpected, rich spectrum of slip behavior occurs on faults has raised numerous questions about the physical processes that control fault slip, as well as the relationship of SSEs to damaging seismic events.

Although SSEs have been observed on many types of tectonic faults (Bürgmann 2018, and references therein), most observations of these phenomena have been made at subduction zones in the circum-Pacific region (Hirose et al. 1999, Dragert et al. 2001, Ohta et al. 2006, Wallace & Beavan 2010, Radiguet et al. 2012, Dixon et al. 2014). One of these, the Hikurangi subduction zone, located offshore of and beneath New Zealand's North Island, has been particularly noteworthy for the sheer diversity of SSE types that occur there (in terms of depth, duration, magnitude, and recurrence interval) and the relationship of SSEs to earthquakes and the locked, seismogenic zone. Moreover, a large number of geophysical, geochemical, and geological variations occur in concert with observed spatial variations in SSE behavior at the Hikurangi subduction zone. Such a setting offers an opportunity to resolve the physical controls on the occurrence of slow slip.

2. TECTONIC SETTING OF THE HIKURANGI SUBDUCTION ZONE

The Hikurangi subduction zone accommodates westward subduction of the Pacific Plate beneath the North Island of New Zealand, along the Hikurangi Trough (**Figure 1**), at the southern end of the >3,000-km-long Tonga-Kermadec-Hikurangi subduction system. In the northern South Island of New Zealand, the subduction zone undergoes a complex transition into the dominantly strike-slip Alpine Fault via the Marlborough Fault System. The portion of the Pacific Plate being subducted at the Hikurangi Trough is composed of the Hikurangi Plateau (**Figure 1*a***), a Cretaceous large igneous province (Mortimer & Parkinson 1996). The Hikurangi Plateau is ~10–15 km thick, making it thicker (and thus more buoyant) than the Cretaceous oceanic crust to the northeast of the plateau (4–9 km thick) (Davy et al. 2008, Mochizuki et al. 2019).

Subduction of the Hikurangi Plateau (**Figure 1**) has caused widespread uplift of the eastern North Island over the last few million years (Litchfield et al. 2007, Nicol et al. 2007), meaning that much of the forearc (the area between the volcanic arc and the trench) is subaerial, and the coastline is in closer proximity to the subduction plate boundary than is the case at most other subduction margins. For example, the plate interface is located at ~12 km depth beneath the east coast of the North Island (**Figure 2**), and the trench is located ~40–120 km offshore. In contrast, at many other well-studied subduction zones (such as Cascadia, Nankai, and northern Japan), the plate boundary is located at 20–60 km depth beneath the coastline, and the trench is typically 100–200 km offshore. In many ways, uplift of much of the North Island as a consequence of Hikurangi Plateau subduction has enabled the use of land-based instrumentation (**Figure 2**) to investigate the spectrum of slip behavior spanning an unusually large depth range of the subduction interface.

The Hikurangi subduction zone undergoes important tectonic transitions along strike. The forearc of the eastern North Island is rotating rapidly (3–4°/Myr) relative to the Australian plate

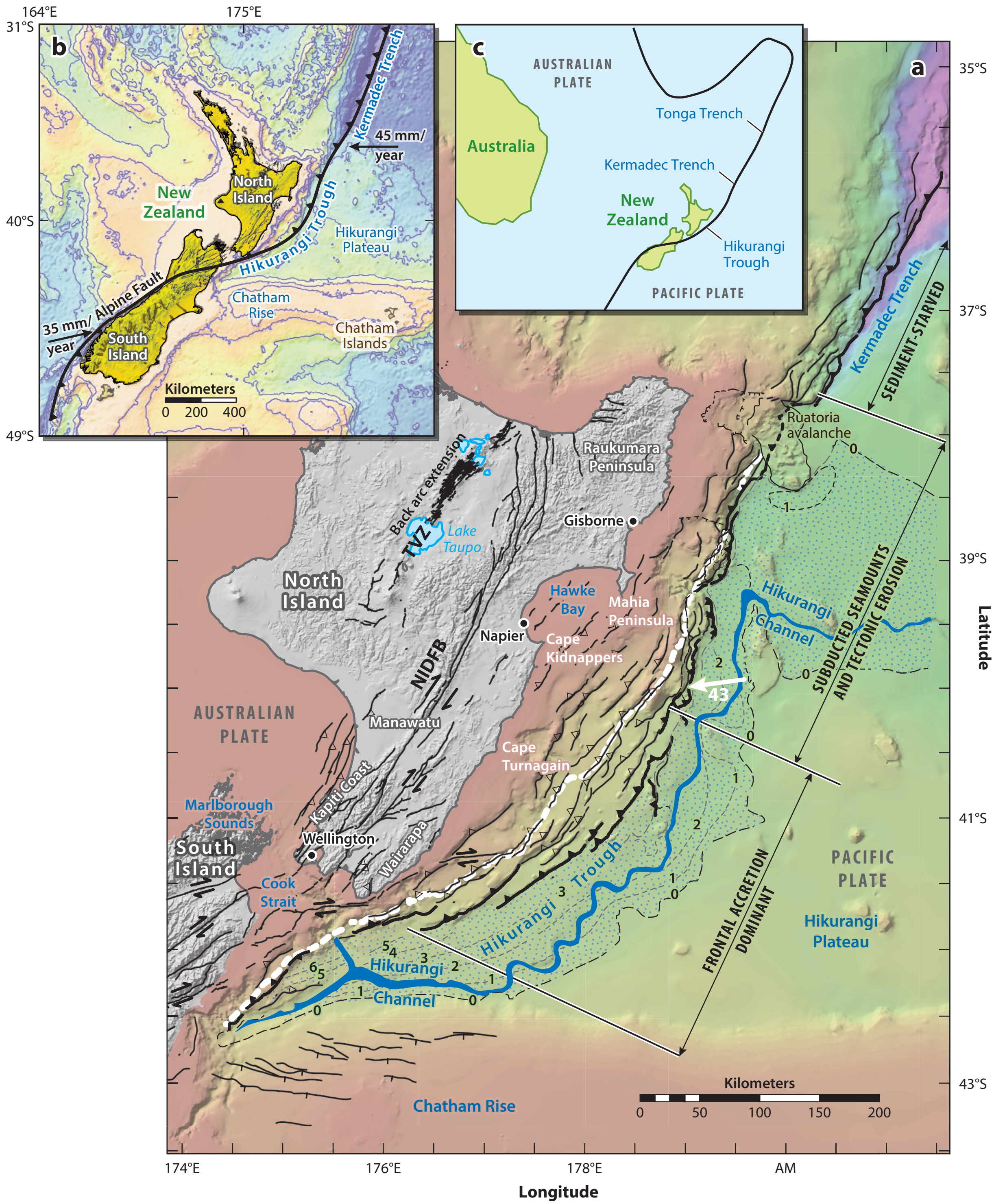

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Figure 1 (*Figure appears on preceding page*)

Tectonic setting of the Hikurangi margin. (*a*) Detailed bathymetry, topography, and active faulting (*black lines*) of the onshore and offshore subduction margin. Dashed contours (labeled in km) indicate trench-fill turbidite thickness (spatial extent shown by *blue stipple pattern*) on the subducting plate (data from Lewis et al. 1998). The bold white dashed line shows the back of the accretionary wedge and the front of a deforming buttress of Cretaceous and Paleogene rocks covered by Miocene to Recent slope basins (data from Lewis et al. 1997; Barnes et al. 1998, 2010). The white arrow shows Pacific-Australia relative plate motion (in mm/year) in the region (data from Beavan et al. 2002). (*b*) Broader-scale New Zealand tectonic setting. (*c*) Inset, regional tectonic framework. Abbreviations: NIDFB, North Island Dextral Fault Belt; TVZ, Taupo Volcanic Zone. Figure adapted from Barnes et al. (2010).

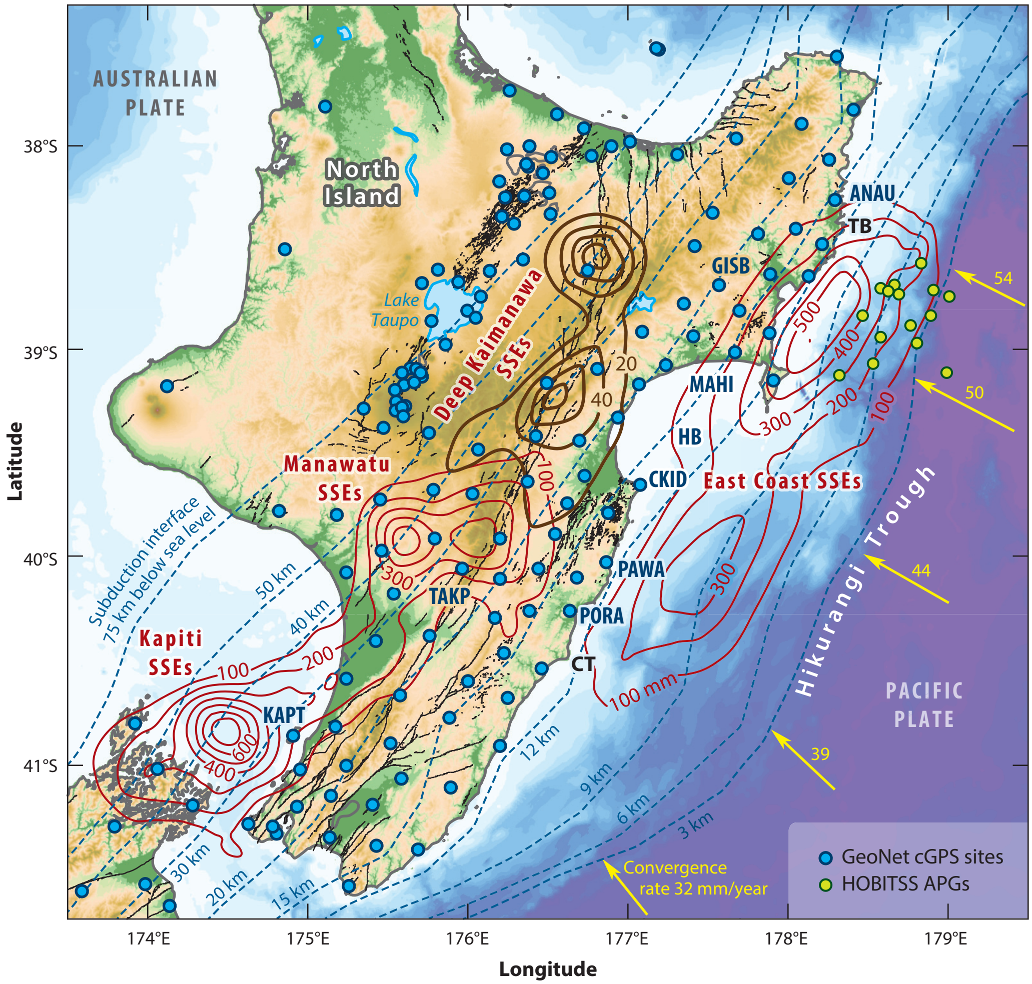

Figure 2

Cumulative slow slip in the North Island for 2002–2014 period. The red contours are in 100-mm contour intervals, while the dark brown contours (20-mm intervals) show the region of small, deep SSEs observed beneath the Kaimanawa ranges in 2006 and 2008 located downdip of the shallow HB SSEs (data from Wallace & Eberhart-Phillips 2013). Labeled dashed dark black lines show the depths to the Hikurangi subduction interface (in km below sea level) (data from Williams et al. 2013), and yellow arrows indicate convergence rates at the Hikurangi Trough (data from Wallace et al. 2012b). Blue dots show the locations of cGPS sites operated by the GeoNet network (**http://www.geonet.org.nz**), and lime green dots are the locations of APGs used in the 2014/2015 HOBITSS experiment (data from Wallace et al. 2016). ANAU, CKID, GISB, KAPT, MAHI, PAWA, PORA, and TAKP are the cGPS sites shown or labeled in **Figures 3** and **4**. Abbreviations: APG, absolute pressure gauge; cGPS, continuously operating global positioning system; CKID, Cape Kidnappers; CT, Cape Turnagain; HB, Hawke Bay; HOBITSS, Hikurangi Ocean Bottom Investigation of Tremor and Slow Slip; SSE, slow slip event; TB, Tolaga Bay.

(Wallace et al. 2004). This rotation, which has been occurring for at least the last few Myr (Nicol et al. 2007), results in back-arc rifting in the central North Island's Taupo Volcanic Zone and transpression in the southern North Island. This rotation also creates a large along-strike change in convergence rate at the Hikurangi Trough, from ~20 mm/year in the south to ~60 mm/year at the northern Hikurangi Trough (Wallace et al. 2004) (**Figure 2**). Although the sense of Australia-Pacific relative plate motion through the North Island is highly oblique, the plate motion is partitioned, with a largely margin-normal sense of plate motion near the Hikurangi Trough. The margin-parallel component of plate motion is accommodated by rotation of the forearc and right-lateral strike-slip in the North Island Dextral Fault Belt (e.g., Beanland & Haines 1998, Wallace et al. 2004). This results in a shift in the sense of long-term relative plate motion on the Hikurangi subduction interface from margin-normal at shallow levels of the plate boundary, which rotates to an oblique angle that is parallel (and equal to) Pacific-Australia plate motion at deeper levels (>25 km depth) (Wallace & Beavan 2010).

There are also large changes in the characteristics of the subduction margin offshore of the east coast of the North Island (e.g., Wallace et al. 2009, Barnes et al. 2010). The sedimentary sequence overlying the Hikurangi Plateau on the subducting Pacific Plate is ~5 km thick at the southern Hikurangi subduction zone and thins northward to <1 km thick at the northern Hikurangi margin (Barnes et al. 2010) (**Figure 1*a***). Numerous seamounts protrude above the thinner sedimentary cover at the northern Hikurangi margin; if such seamounts exist at the southern Hikurangi margin, they are largely buried by the thick sedimentary sequence blanketing the subducting plate. The southern and central Hikurangi margin is the site of a wide (30–70 km), well-developed accretionary wedge (Barnes et al. 2010). The active outer wedge is much narrower (<20 km) at the northern Hikurangi subduction zone, often attributed to tectonic erosion due to seamounts regularly impacting the margin.

3. THE MENAGERIE OF SLOW SLIP IN NEW ZEALAND

3.1. Geodetic Observations of Slow Slip at the Hikurangi Margin

New Zealand's network of continuously operating global positioning system (cGPS) instruments and seismometers, operated by GeoNet (**https://www.geonet.org.nz**), has enabled detection of SSEs and related seismicity at the Hikurangi subduction zone. The cGPS and seismic network on the Hikurangi margin began construction in 2002 (Gale et al. 2015), and the first SSE was promptly discovered in October 2002 using data from a cGPS site in the northeastern North Island near the town of Gisborne (Douglas et al. 2005). Numerous observations of SSEs along the length of the subduction margin soon followed (Wallace & Beavan 2006, 2010; Beavan et al. 2007; Wallace & Eberhart-Phillips 2013; Wallace et al. 2012a, 2014, 2016, 2017, 2018; Bartlow et al. 2014; Koulali et al. 2017). Overall, one of the most striking features of Hikurangi SSEs observed thus far is their diversity of depths, duration, magnitude, and recurrence characteristics, which vary strongly from north to south (**Figures 2** and **3**).

Determining the distribution and magnitude of slip in SSEs is usually done by inverting surface displacements [from GPS, interferometric synthetic aperture radar (InSAR), or other data] for parameters describing the subsurface deformation source. Such inversions typically rely on analytical equations that relate surface displacements to dislocations in an elastic half-space, although other approaches can be used as well. For SSEs at subduction zones, the subduction zone source fault geometry is typically defined by the user, and the amount of slip at patches or nodes on the fault is inverted for. Static displacements of GPS sites over a specific period of time can be inverted to obtain a total slip amount in a given event or during stages of the event (e.g., Wallace & Beavan 2010). However, to develop a full understanding of the SSE evolution,

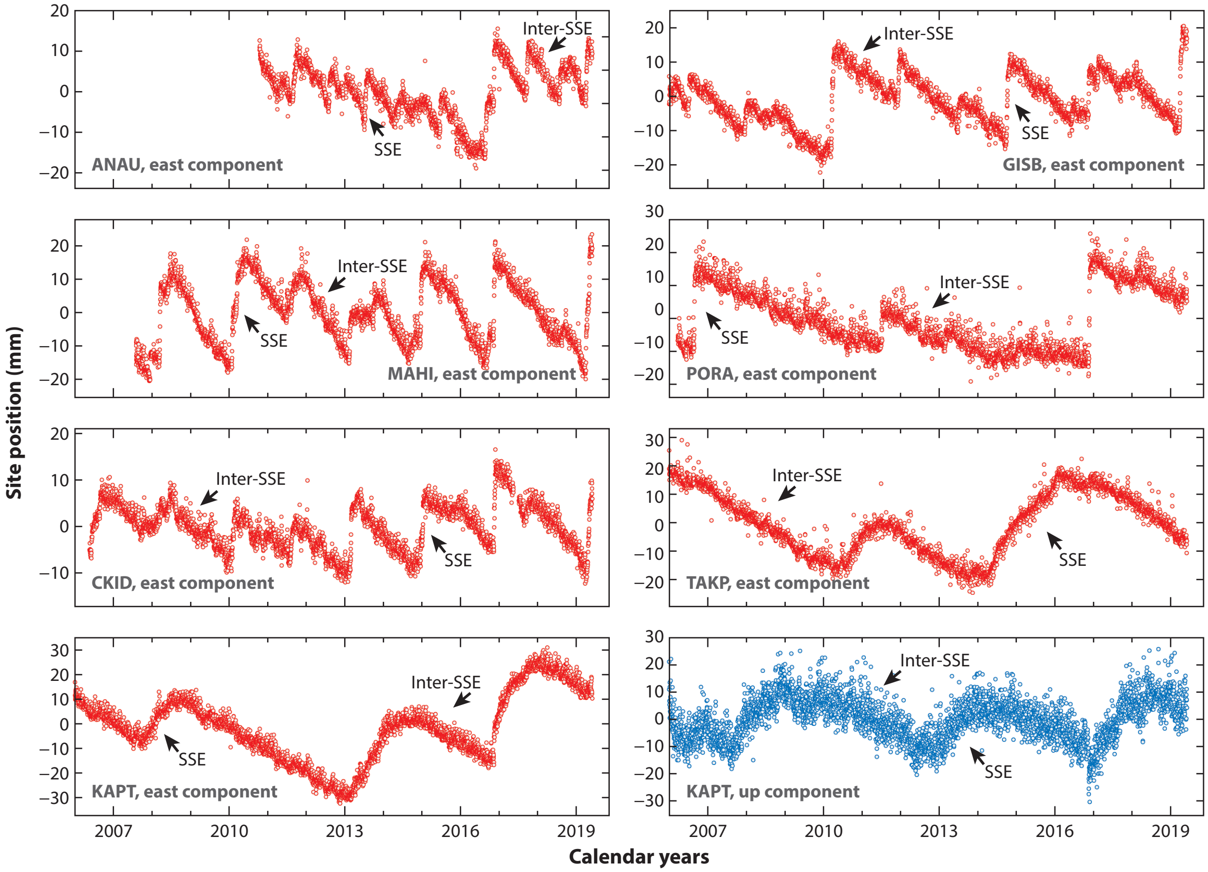

Figure 3

Example cGPS site time series from the Hikurangi margin (2006 to mid-2019) showing short-term, shallow SSEs (ANAU, GISB, MAHI, PORA, CKID), and deep, long-term SSEs (TAKP, KAPT). Site locations are shown on **Figure 2**. Abbreviations: cGPS, continuously operating global positioning system; SSE, slow slip event. Data from **https://www.geonet.org.nz**.

time-dependent approaches can be used to invert GPS time series for a temporally evolving slip model (e.g., Bartlow et al. 2014). Geodetic studies of Hikurangi subduction slow sip events have employed both of these types of approaches.

3.1.1. Shallow slow slip events at the northern and central Hikurangi subduction zone. SSEs at the northern and central Hikurangi margin are typically observed at cGPS sites along the east coast of the North Island, particularly in the Hawkes Bay and Gisborne regions (**Figures 1–4**). The horizontal displacement at cGPS sites during these events increases in magnitude toward the coast and is often accompanied by subsidence (up to 1 cm) at some of the coastal sites; together, this indicates that the vast majority of slip on the plate boundary is located offshore, at depths of less than 15 km (Douglas et al. 2005, Wallace & Beavan 2010, Wallace et al. 2012a). To expand the SSE observations offshore, the Hikurangi Ocean Bottom Investigation of Tremor and Slow Slip (HOBITSS) experiment was undertaken in 2014 offshore from Gisborne. HOBITSS involved deployment of 24 seafloor absolute pressure gauges (APGs) and 15 ocean-bottom seismometers (OBSs) (lime green dots show APG locations in **Figure 2**), with an aim to resolve seismicity and

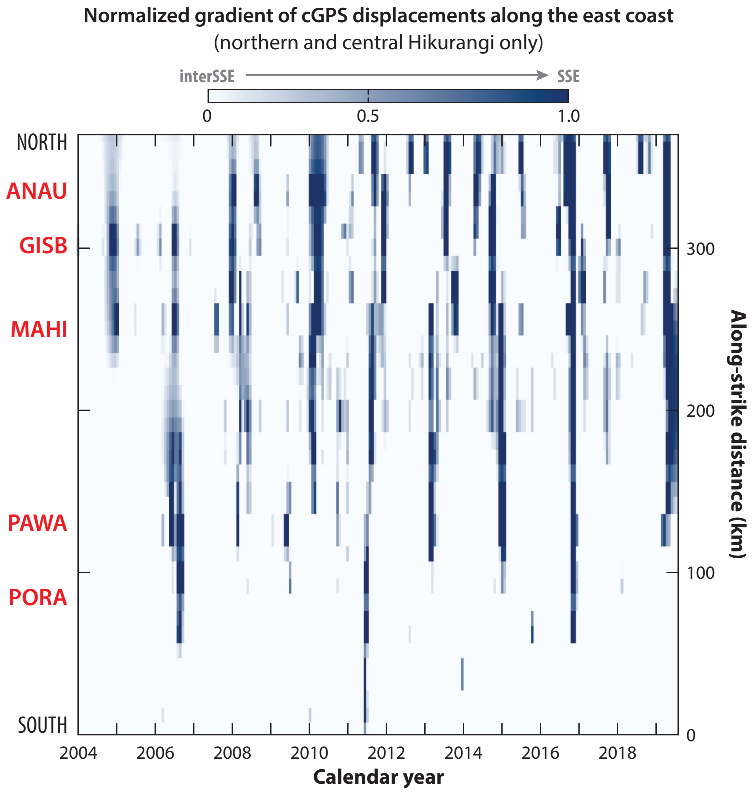

Figure 4

Change in rate of motion at GeoNet cGPS sites along the east coast of the North Island, from 2004 to mid-2019 (*x*-axis), illustrating the occurrence of shallow east coast SSEs during that period. The rate of change is shown in terms of a normalized gradient, with 0 = minimum rate of change (e.g., the interslow slip velocity) and 1 = the maximum rate of change. The time series positions are projected onto a line running along the strike of the margin (*y*-axis); the data are filtered in time with a 17-day gaussian filter. Darker colors show periods with the fastest rates of position change in the cGPS time series (e.g., times of slow slip). Site names labeled in red on the left axis show the position of cGPS sites labeled on **Figure 2** along the strike-line. Abbreviations: cGPS, continuously operating global positioning system; SSE, slow slip event. Figure provided by Stephen Bannister, GNS Science. Data from **https://www.geonet.org.nz**.

vertical deformation of the seafloor during offshore SSEs. The APGs continuously record absolute pressure at the seafloor, so if the seafloor moves up or down due to an earthquake or SSE, this deformation will be recorded as a pressure decrease or increase, respectively. During the deployment, a large SSE occurred directly beneath the network in late September 2014 and produced ∼1–5 cm of vertical displacement of the seafloor over the course of a few weeks (Wallace et al. 2016) (**Figure 5**). Based on the vertical displacements inferred from the APG data, it appears that northern Hikurangi SSEs can continue offshore to within at least 2 km of the seafloor and possibly all the way to the trench. The 2014 HOBITSS experiment was the first to clearly demonstrate that APGs are a viable tool to resolve centimeter-level vertical deformation of the seafloor during SSEs at offshore subduction zones.

In general, these shallow east coast SSEs typically occur every 1–2 years (**Figure 3**), although there is some variability in the frequency of SSE occurrence along the offshore margin (**Figure 4**). For the SSE patch offshore from Cape Turnagain (**Figure 2**), SSEs appear to recur less frequently

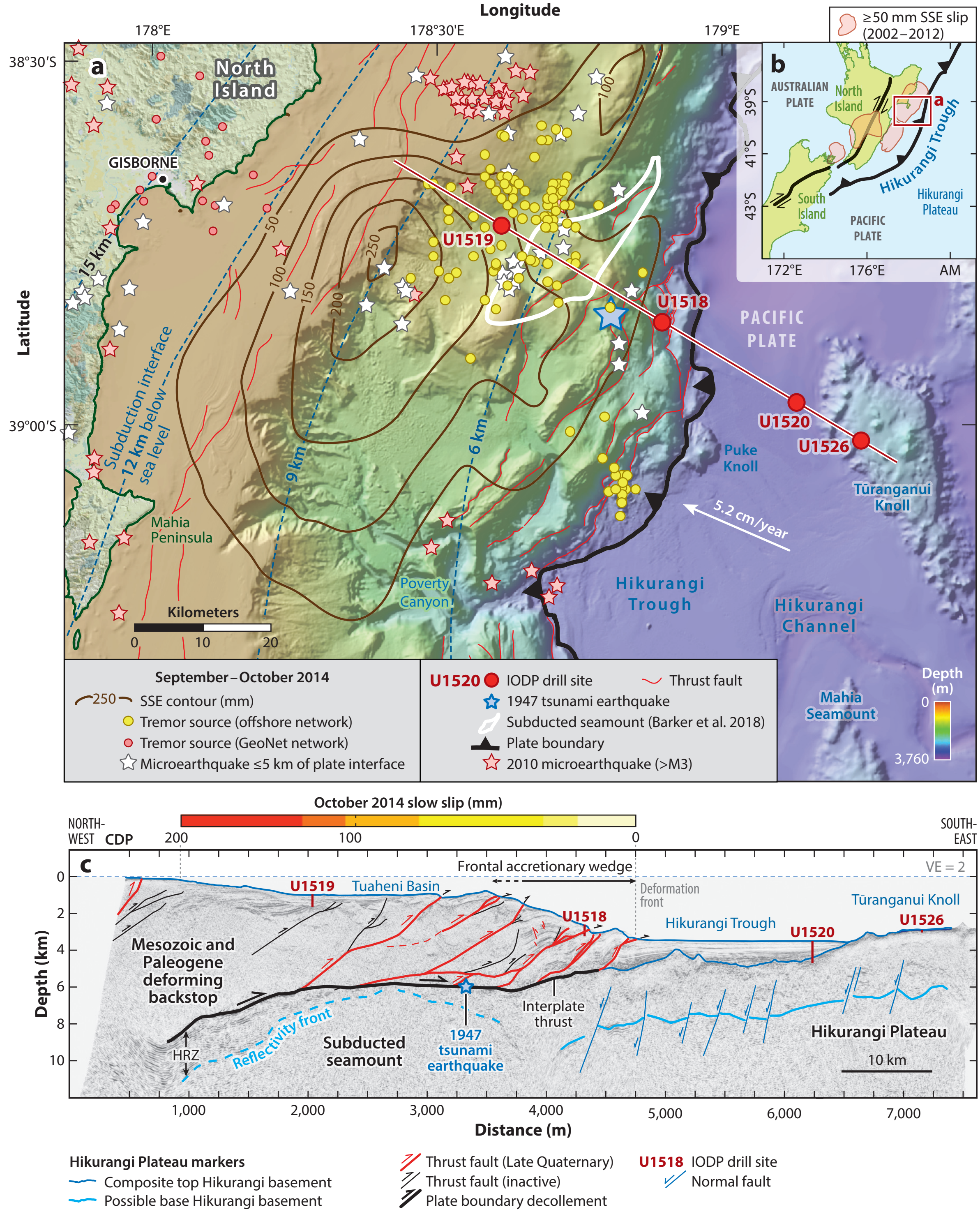

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Figure 5 (*Figure appears on preceding page*)

Tectonic setting of slow slip at the northern Hikurangi subduction margin. (*a*) Bathymetric map showing the distribution offshore slow slip during the 2014 SSE (SSE from Wallace et al. 2016), seismic tremor (low-frequency energy bursts in the 4–10-Hz frequency range), and microearthquakes (data from Todd & Schwartz 2016, Todd et al. 2018) associated with three SSEs. Dashed blue lines show approximate depth to the plate interface (data from Williams et al. 2013). The solid white outline shows the location of a subducted seamount inferred from seismic reflection images and magnetic data (Barker et al. 2018). (*b*) Pacific-Australia plate boundary showing in pink the approximate distribution of cumulative slow slip between 2002 and 2012 (data from Wallace et al. 2012a). The red-outlined box shows the location of the map in panel *a*. (*c*) Interpretation of seismic profile 05CM-04 (from Barker et al. 2018, Barnes et al. 2020). The color scale at the top of the panel shows slip distribution of the October 2014 SSE (data from Wallace et al. 2016). Abbreviations: CDP, common depth point; HRZ, high-amplitude reflective zone; IODP, International Ocean Discovery Program; SSE, slow slip event; VE, vertical exaggeration. Figure adapted from Barnes et al. (2020).

than elsewhere, approximately every 5 years (e.g., in 2006, 2011, and 2016) (Wallace et al. 2012a, 2017) (**Figures 3** and **4**, near site PORA). In contrast, north of Gisborne, near Tolaga Bay (**Figure 2**), SSEs occur more frequently than elsewhere along the margin, typically 1–2 events per year (near site ANAU on **Figures 3** and **4**). In many cases, sequences of large, shallow SSEs cluster in time, such as during 2011 when much of the east coast SSE region underwent slip (Wallace et al. 2012a) (**Figure 4**). Despite contrasts in interevent times, the shallow east coast SSEs typically last 2–3 weeks, although there have been some exceptions where they have lasted a few months. There is also a large range of magnitudes for the shallow east coast events—including some very large SSEs (equivalent $M_w > 7.0$) such as those offshore from Gisborne in September 2014 (Wallace et al. 2016) and January 2010 (Wallace & Beavan 2010). On the other end of the spectrum, the equivalent moment magnitude of smaller detected events can be as small as M_w 6.0–6.5, particularly for the very frequent events near ANAU and northward (**Figures 3** and **4**).

3.1.2. Deep slow slip events at the southern and central Hikurangi margin.

We have observed two classes of deep subduction SSEs at the Hikurangi margin. The first are the Kapiti and Manawatu SSEs (**Figure 2**), which are long-lived (lasting 1–2 years) and recur approximately every 4–5 years (**Figure 3**, TAKP and KAPT). Kapiti and Manawatu SSEs typically release a large amount of stored moment, resulting in >30 cm of slip on the plate boundary, equivalent to an $M_w > 7.0$ earthquake. The Kapiti SSEs occur where the plate interface is 25–50 km depth, while Manawatu SSEs have a wider along-dip extent, spanning 15–50 km depth (Wallace & Beavan 2010, Wallace et al. 2012a, Bartlow et al. 2014) (**Figure 2**). The horizontal surface displacement observed at some GPS sites during these events is large—usually 30–40 mm, and with a similar magnitude of vertical displacements at some sites (**Figure 3**, KAPT).

Past Kapiti SSEs have occurred in 2003, 2008, 2013, and late 2016–2018—the latter was triggered by the November 14, 2016, M_w 7.8 Kaikōura earthquake (Wallace et al. 2018), which appears to have brought the Kapiti SSE recurrence forward in time by a couple of years. Manawatu SSEs have been observed at cGPS sites in 2004/2005, 2010/2011, and 2014/2015. Manawatu SSEs often (but not always) occur just following a Kapiti SSE; for example, the 2004/2005 Manawatu SSE (Wallace & Beavan 2006) immediately followed the 2003 Kapiti event. Likewise, the 2014/2015 Manawatu SSE followed the 2013 Kapiti SSE, and time-dependent inversions suggest that the 2013 Kapiti SSE migrated northward into the Manawatu SSE source region (Wallace et al. 2014). These observations suggest a tendency for southern Hikurangi SSEs to propagate northward, along strike from the Kapiti into the Manawatu region. However, this is not clearly the case for the 2008 Kapiti and 2010–2011 Manawatu SSEs, nor for the 2016–2018 Kapiti SSE. Notably, the SSE source region between the Kapiti and Manawatu region likely ruptured only during the 2003–2005 and 2013–2015 sequence of deep SSEs (Wallace & Beavan 2010, Wallace et al. 2014). This suggests the possibility of a roughly 10-year rupture cycle for the SSE patch between the

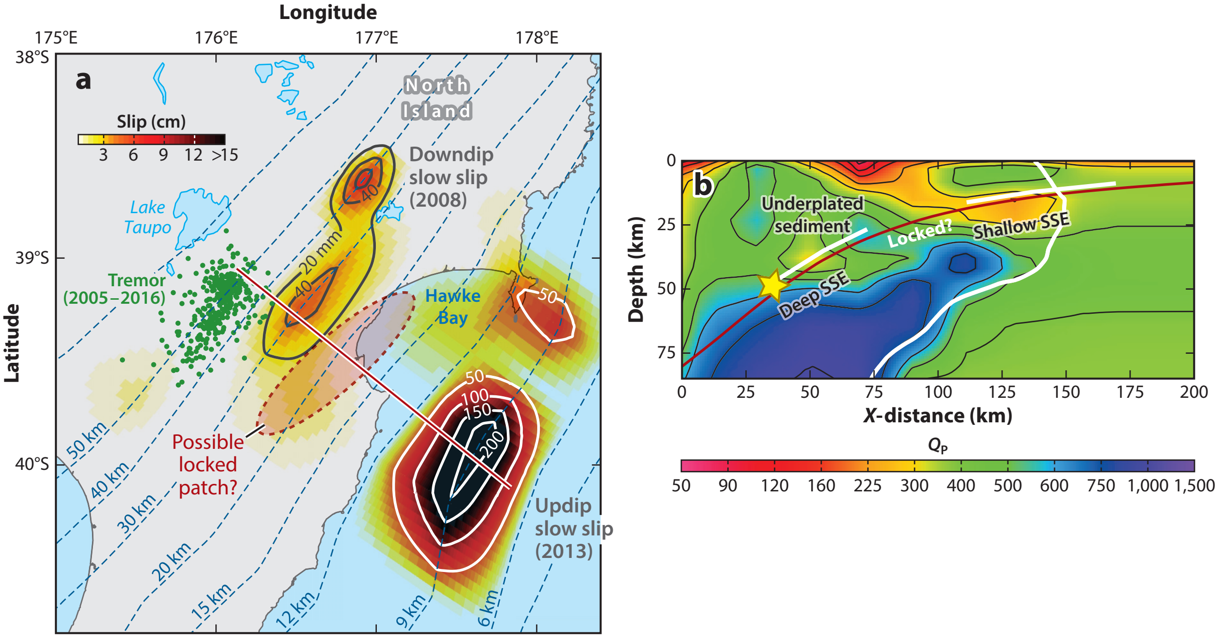

Figure 6

(*a*) Two representative SSEs (in 2008 and 2013) at the central Hikurangi subduction zone (Wallace & Eberhart-Phillips 2013) and tremor (2006–2015; Romanet & Ide 2019), where we observe a large amount of downdip variability in SSE, tremor, and locking behavior (area of possible locking between the two slow slip patches shaded in *pink*. Hot colors show slip magnitudes on the plate interface during the SSEs, with labeled 20-mm contours for the smaller and deeper 2008 event and 50-mm contours for the larger, shallower, and shorter 2013 event. (*b*) Cross-section (location indicated by *red line* in panel *a*) showing Q_P (quality factor of P-wave, the inverse of attenuation), labeled with positions of deep and shallow SSE areas, interpreted underplated sediment, and approximate tremor location (*yellow star*). Panel adapted from Eberhart-Phillips et al. (2008). Abbreviation: SSE, slow slip event.

recurrent Kapiti and Manawatu SSE patches, facilitating northward propagation of Kapiti SSEs into the Manawatu source when this occurs. Observations of future events will help clarify this relationship.

The second type of deep subduction SSEs at the Hikurangi subduction zone are observed beneath the Kaimanawa ranges at 30–40 km depth, <75 km downdip of the shallow SSEs that occur in the Hawkes Bay region (Wallace & Eberhart-Phillips 2013) (dark brown contours in **Figure 2**; **Figure 6**). This class of SSEs were most clearly observed in 2006 and 2008. They have a shorter duration than other deep Hikurangi margin SSEs, usually lasting 2–3 months. They are much smaller than the large Kapiti and Manawatu deep SSEs, resulting in less than 5 mm of surface displacement in each event, likely arising from ∼2–5 cm of slip on the plate interface.

3.1.3. Influence of elastic heterogeneity on geodetic inversions of Hikurangi slow slip events. Most published inversions of SSEs, interseismic coupling, and coseismic deformation at subduction zones assume that the faults are embedded in a uniform, elastic half-space. However, strong elastic property contrasts exist at subduction zones, where a rigid, high-velocity oceanic slab is juxtaposed against a less rigid forearc. This contrast is particularly marked for offshore subduction margins, where the outer forearc is composed of recently accreted, low-velocity sediments (e.g., Kamei et al. 2012). The influence of this velocity contrast on inversion of surface displacements for Hikurangi slow slip has been addressed by Williams & Wallace (2015, 2018) using both onshore and offshore geodetic data, with elastic properties constrained by a nationwide three-dimensional (3D) seismic velocity model (Eberhart-Phillips et al. 2010). For deeper SSEs, such as the Manawatu SSEs, the heterogeneous elastic models require ∼20% less slip on the plate interface (compared to uniform elastic models) to reproduce the observed surface displacements (Williams & Wallace 2015). This is due to greater focusing of the resulting deformation into the less-rigid hanging wall. In contrast, inversions for shallow, offshore SSE slip (using onshore and offshore geodetic data) that incorporate realistic elastic properties require ∼30–40% more slip on the plate boundary to fit the surface displacement data (Williams & Wallace 2018). This contrasting result for shallow SSEs is due to the influence from vertical body forces on predicted vertical displacements in the heterogeneous models near the trench, which causes a reduction in the amount of vertical surface deformation for a given amount of slip (compared to homogeneous elastic models). Overall, SSE slip models incorporating realistic elastic property variations provide more accurate SSE slip estimates and result in much-improved fits to the GPS data (compared to homogeneous models) at the Hikurangi margin (Williams & Wallace 2015, 2018). Such models are important to implement, as they more accurately quantify the role of SSEs in accommodating overall plate motion budgets at subduction zones.

3.2. The Seismic Expression of Hikurangi Slow Slip

The seismic signature of slow slip has been a major focus in the field of transient SSEs at subduction zones (Rogers & Dragert 2003, Obara et al. 2004, Delahaye et al. 2009, Brudzinski et al. 2010). For example, the rich and varied relationships between tremor, low-frequency earthquakes, and slow slip have revealed important details about the SSE process in places such as Cascadia and southwest Japan (Nankai Trough) (Obara & Hirose 2006, Shelly et al. 2006, Wech & Creager 2011) and have led to Nankai and Cascadia SSEs being referred to as episodic tremor and slip events. However, evidence for tremor signatures in association with slow slip at the Hikurangi margin has proven more elusive than for many other subduction zones. There is some indication from both onshore and offshore seismometers for tremor during shallow, northern Hikurangi SSEs (Kim et al. 2011, Todd & Schwartz 2016, Todd et al. 2018) (**Figure 5**), and in relationship to the deeper Manawatu and Kaimanawa SSEs (Ide 2012, Romanet & Ide 2019) (**Figure 6**), as well as tremor triggered by teleseismic earthquakes (Fry et al. 2011). Enhanced levels of seismicity are a far more common seismic expression of SSEs at the Hikurangi subduction zone—these episodes can occur during or just after the SSEs (e.g., Reyners & Bannister 2007, Delahaye et al. 2009, Wallace et al. 2012a, Bartlow et al. 2014, Jacobs et al. 2016, Shaddox & Schwartz 2019, Warren-Smith et al. 2019, Yarce et al. 2019). The prevalence of seismicity during SSEs at the Hikurangi margin, rather than tremor (as observed in Cascadia and Nankai), may reflect a variety of factors, including the thermal structure of the margin (Yabe et al. 2014), the scale and physical characteristics of frictional heterogeneities in the SSE regions (Wallace et al. 2012a), and attenuation characteristics within the upper plate that can influence whether tremor signatures are recorded at the surface (Todd & Schwartz 2016).

Investigations of tremor in the Manawatu and Kaimanawa SSE regions (Ide 2012, Romanet & Ide 2019) (**Figure 6**) have revealed a region of tremor estimated to occur at 45–50 km depth on or near the subduction interface, located just northeast of the Manawatu SSE source, and along the downdip edge of the smaller, deep SSEs observed beneath the Kaimanawa ranges (Wallace & Eberhart-Phillips 2013) (**Figure 6**). This deep, central Hikurangi tremor occurs approximately yearly, during both SSE and non-SSE periods, with some episodes coinciding with the 2010/2011

Manawatu SSE and the 2006 and 2008 Kaimanawa SSEs (Romanet & Ide 2019). Given the more frequent tremor episodes observed here, it is possible that smaller SSEs below the current geodetic network detection threshold also occur in this area of the central Hikurangi subduction zone.

Tremor coinciding with shallow SSEs in the Gisborne region has been detected with both onshore GeoNet seismic stations (Kim et al. 2011, Todd & Schwartz 2016) and temporary OBS networks (Todd et al. 2018) (**Figure 5**). Bursts of tremor associated with large, shallow SSEs in 2010 and 2014 have been located near the downdip edge of the shallow SSE region, extending landward to where the subduction interface is at ∼20 km depth (Kim et al. 2011, Todd & Schwartz 2016). A large-scale deployment of OBS instruments during a late 2014 SSE (the HOBITSS experiment) enabled identification of tremor in the offshore portion of the shallow SSE region (Todd et al. 2018). In this case, the offshore tremor was more prevalent later in the SSE and mostly clustered along the downdip edge of a subducting seamount (Barker et al. 2018, Todd et al. 2018). Many other tremor episodes have been noted during smaller, shallow SSEs at the northern Hikurangi margin (Todd & Schwartz 2016).

Rates of seismicity increase markedly during many of the large, shallow, east coast SSEs. Of particular note is the southern end of the shallow SSE region, offshore from Porangahau and Cape Turnagain (**Figures 2**, **7**), which experiences large SSEs approximately every 5 years (2006, 2011, and 2016) (Wallace et al. 2012a, 2017). These SSEs are accompanied by significantly increased levels of seismicity, in some cases with earthquakes up to M_w 6.0 (Wallace et al. 2012a, 2017; Bartlow et al. 2014). During the June/July 2011 Porangahau SSE, the seismicity clearly migrated along strike with time, tracking the migration of the SSE as defined by onshore geodetic stations (Wallace et al. 2012a) (**Figure 7**). Deep Kapiti SSEs are also accompanied by higher rates of

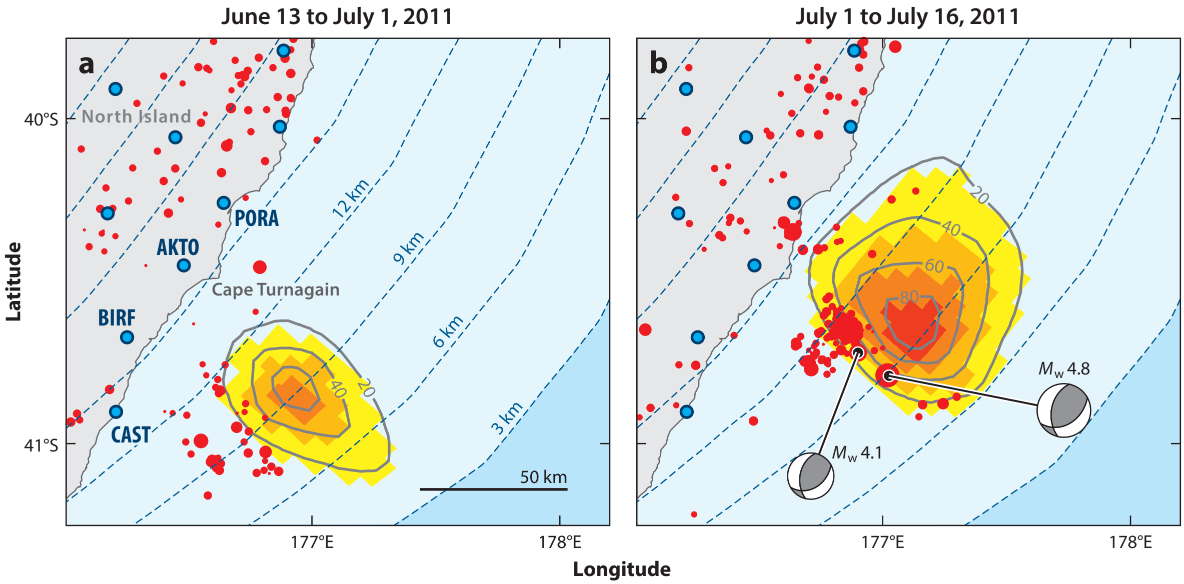

Figure 7

SSE slip distribution (contours labeled in mm) and seismicity associated with the June–July 2011 SSE sequence for the time periods (*a*) June 13 to July 1 and (*b*) July 1 to July 16. Moment tensor solutions (**https://www.geonet.org.nz/data/types/eq_catalogue**) are shown for two of the events (M_w 4.8 and M_w 4.1), indicating thrust faulting with a small component of strike-slip. Dashed blue contours show depth to the subduction interface (below sea level). Abbreviation: SSE, slow slip event. Figure adapted from Wallace et al. (2012a).

seismicity in the lower North Island region, often occurring on intraslab faults, with events as large as M_w 6.3 (Jacobs et al. 2016, Reyners & Bannister 2007, Wallace et al. 2014).

Some exciting observations of temporal variations in earthquake characteristics throughout the northern Hikurangi SSE cycles have recently been made that may yield insight into the role of fluid pressure buildup, release, and migration during the SSE cycle (Shaddox & Schwartz 2019, Warren-Smith et al. 2019). Using OBS data from the HOBITSS deployment in 2014–2015, Warren-Smith et al. (2019) showed that focal mechanisms of earthquakes within the subducting Pacific slab undergo systematic changes with time, reflecting changes in relative magnitudes of the principal stresses throughout four SSE cycles at the northern Hikurangi margin. They suggested that these changes reflect buildup and release of fluid pressure during the SSE cycle on faults within the slab, with the important implications that the fluids may migrate into the SSE region and that fluid pressure cycling and stress switching within the slab influences the timing of SSEs on the subduction interface. Shaddox & Schwartz (2019) used the HOBITSS OBS data to resolve burst-type repeating earthquakes during the two months following the September/October 2014 SSE, located within the upper plate. They interpret this protracted sequence of earthquakes as a consequence of overpressured fluid within the SSE source region being released into the upper plate along fault networks located above a subducting seamount, leading to a complex interplay between seismic and aseismic behavior.

3.3. Relationship Between Slow Slip, Interseismic Coupling, and Subduction Earthquakes on the Hikurangi Subduction Zone

Campaign GPS measurements acquired intermittently at survey points throughout New Zealand over the last 25 years (Beavan et al. 2016) have enabled resolution of a time-averaged view of interseismic coupling on the Hikurangi subduction interface beneath the North Island (Wallace et al. 2004, 2012b) (**Figure 8*a***). Interseismic coupling occurs when the plates lock together during the hundreds to thousands of years between large megathrust earthquakes (e.g., the interseismic period). This leads to the accrual of elastic strain within the surrounding crust, which is eventually relieved in earthquakes. Surface displacements (centimeters to millimeters per year) resulting from this elastic strain accumulation are measurable with GPS and can be used to resolve where, and at what rate, the interseismic coupling (or locking) occurs.

Generally, the northern and central Hikurangi SSEs occur in a region of the shallow interface that is currently dominated by interseismic creep, with some possible locked patches in the offshore region. The presence of locking offshore is not well resolved with land-based GPS measurements. In contrast, the Kapiti and Manawatu SSE sources follow the deep transition from interseismic coupling to aseismic creep at the southern Hikurangi margin, outlining the locked zone of the plate boundary remarkably well (**Figure 8*a***). The position of the Kapiti and Manawatu SSEs along the locked to creeping transition is consistent with the idea that SSEs represent transitional frictional behavior. Likewise, the velocities of cGPS sites during the period between SSEs can be inverted (Wallace & Beavan 2010) to reveal the distribution of coupling and elastic strain accumulation between SSEs (e.g., inter-SSE coupling). We note that it is not possible to resolve inter-SSE coupling (or other deformation rate changes during the slow slip cycle) from the intermittent campaign GPS measurements, as the resolution of temporal sampling in the GPS campaigns is too coarse (e.g., every few years or more); cGPS measurements (daily time series) are required for this. The Kapiti, Manawatu, and east coast SSE source regions appear to be nearly 100% coupled during the period between SSEs (**Figure 8*b***). In contrast, the interseismic coupling models based on campaign GPS velocities averaged over the last 20 years indicate that the interface in these SSE source regions is largely creeping at decadal timescales (**Figure 8*a***). This

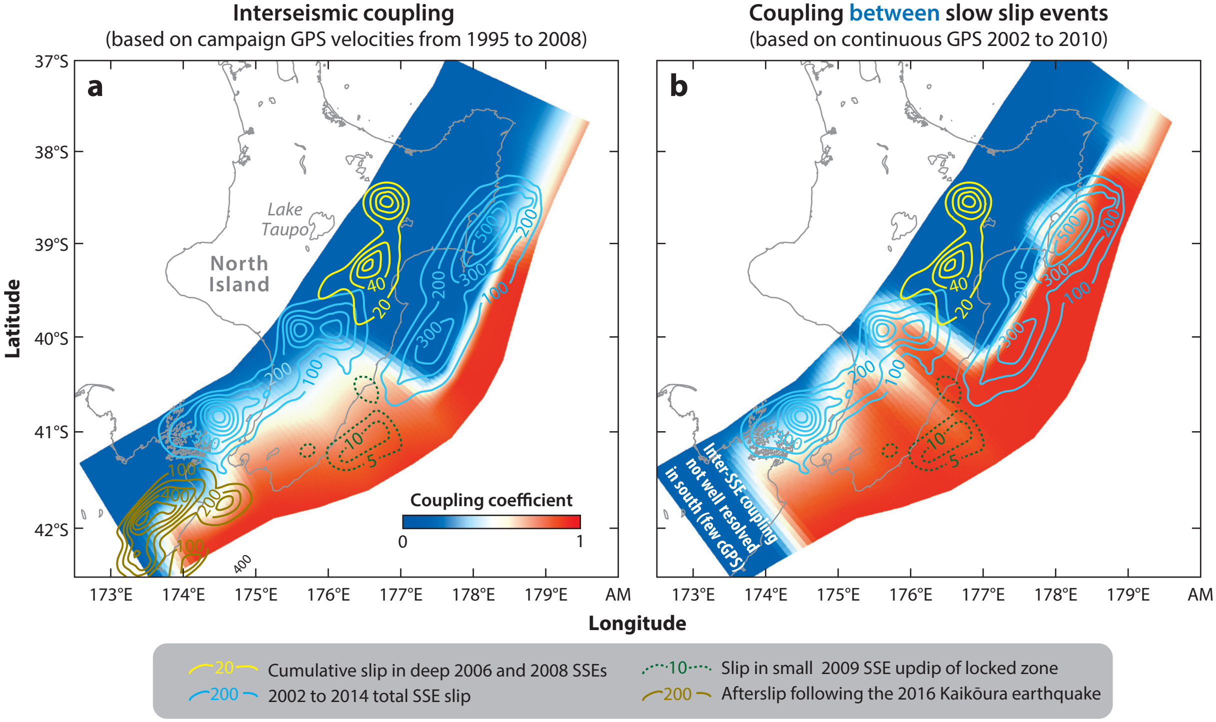

Figure 8

(*a*) Interseismic coupling based on campaign GPS velocities (1995–2008), shown in terms of coupling coefficient (Wallace et al. 2012b). The interseismic coupling coefficient is a purely kinematic quantity, $\phi_{ic} = 1 - (V_c/V)$, where V is the long-term averaged slip rate on the fault (over many earthquake cycles) and V_c is the short-term creep rate. If $\phi_{ic} = 0$, then this region of the fault is creeping at the full long-term slip rate; if $\phi_{ic} = 1$, there is no creep in the interseismic period. In the case where ϕ_{ic} is neither 0 nor 1, one could interpret it as a spatial and/or temporal average of creeping and noncreeping patches (Scholz 1990, Lay & Schwartz 2004). Green, brown, blue, and yellow contours represent different SSE episodes and/or different periods of cumulative SSE slip (labeled in millimeters; from various publications discussed in this paper). (*b*) Coupling on the interface (in terms of coupling coefficient) for the periods between SSEs (Wallace & Beavan 2010). We note that the inter-SSE coupling is not well resolved in the northern South Island due to a lack of cGPS instruments. Abbreviations: cGPS, continuously operating global positioning system; GPS, global positioning system; SSE, slow slip event.

suggests that SSEs accommodate the majority of plate motion within the SSE source regions at the Hikurangi subduction zone. The yearly rate of moment deficit accumulation due to coupling on the Hikurangi subduction interface is ~40% higher during the period between SSEs (**Figure 8*b***) than it is averaged over the last 20 years (Wallace & Beavan 2010) (**Figure 8*a***). Overall, it is clear that SSEs play a major role accommodating the plate motion budget at the Hikurangi subduction zone.

For some Hikurangi SSEs observed to date, the relationship to interseismic coupling is less clear-cut. A small SSE (involving a few centimeters of slip on the plate interface) ruptured off the Wairarapa coast in 2009 within the strongly locked zone, as observed at cGPS sites CAST and TEMA (Wallace et al. 2012a) (green dashed lines in **Figure 8**). This SSE is located well south of the region that typically ruptures in shallow SSEs and also south of the along-strike transition from creep at central Hikurangi to deep locking at southern Hikurangi. Subseafloor observatories at the offshore Nankai subduction zone have revealed similar, small SSEs located updip of the locked, seismogenic zone at the Nankai Trough (Araki et al. 2017). It is plausible that both the 2009

Wairarapa SSE and the shallow Nankai Trough SSEs are occurring within the updip frictional transition from seismic to aseismic behavior. The location of this transition is offshore in both locations and is thus not resolvable with the existing, land-based geodetic data.

The relationship of small SSEs occurring on the deeper portion of the central Hikurangi plate boundary (e.g., Kaimanawa SSEs; **Figure 6**) to the broader distribution of coupling and SSEs elsewhere is also unclear (yellow contours in **Figure 8**). These Kaimanawa SSEs are smaller and shorter in duration (lasting less than a couple of months) than other deep Hikurangi SSEs (Kapiti and Manawatu). They occur in a region of aseismic creep and are located ∼75 km downdip from the shallow (<15 km depth) Hawkes Bay SSEs. These deeper SSEs coincide with a region of low Q_P (high attenuation; Q_P is the inverse of P-wave attenuation) and high V_P/V_S (V_P = P-wave velocity; V_S = S-wave velocity) on the subduction interface, interpreted to be a region of subducted, underplated sediment where fluid pressure may be high (Wallace & Eberhart-Phillips 2013) (**Figure 6**). Between these deep and shallow SSE regions in Hawkes Bay, a large amount of contractional strain (derived from GPS measurements) suggests that there may be a small locked patch between the two SSE regions (Dimitrova et al. 2016) (pink ellipse in **Figure 6**). It may be that downdip changes in plate interface properties at the central Hikurangi margin lead to multiple SSE regions at different depths, with different SSE characteristics, and with intervening areas of interseismic coupling.

In March of 1947, an $M_w \sim 7.2$ earthquake occurred near the trench offshore of Gisborne (blue star in **Figure 5**) in an area where large, shallow SSEs are now observed. The earthquake was located near the trench; had a reverse-faulting mechanism; generated a larger tsunami (8–10 m) than expected, given the earthquake's magnitude (Doser & Webb 2003); and had many characteristics consistent with being classified as a so-called tsunami earthquake (e.g., Kanamori & Kikuchi 1993). Tsunami earthquakes are thought to occur in areas of conditional frictional stability, similar to SSEs. Further south, there is also strong paleoseismic evidence for repeated subduction earthquakes ($M_w \sim 8$) offshore the Hawkes Bay region (Clark et al. 2019), coinciding with areas currently undergoing shallow SSEs and interseismic creep (**Figure 6**). Both the Gisborne and Hawkes Bay examples of overlapping large earthquake and SSE source regions suggest that shallow SSE source areas and apparently creeping, shallow interfaces may also be capable of hosting large earthquakes—such a possibility has important seismic and tsunami hazard implications.

4. EPISODIC SLOW SLIP BEHAVIOR ELSEWHERE IN NEW ZEALAND

Although the Hikurangi subduction zone is the most well-known source of slow slip in New Zealand, there is also some evidence for transient, episodic slip on other faults in the New Zealand region. New Zealand has a second subduction zone, the Puysegur Trench, where the Australian plate subducts eastward beneath the southwestern South Island, offshore Fiordland (**Figure 1*b***). Although the cGPS network in the Fiordland region is sparse, InSAR data reveal evidence for an aseismic slip event in the George Sound area that appears to have been triggered by the 2009 M_w 7.8 Dusky Sound earthquake, ∼150 km southwest of George Sound (Hamling & Hreinsdóttir 2016). This triggered slip event coincides with a region of afterslip following the 2007 M_w 6.8 George Sound earthquake, so it may represent rejuvenated afterslip or triggered slow slip. In the North Island, InSAR data acquired between 2004 and 2005 revealed evidence that the Wellington Fault (part of the North Island Dextral Fault Belt; **Figure 1*a***) was offset by ∼2 cm during the 2004/2005 Manawatu SSE (Hamling & Wallace 2015). This is the first evidence that subduction SSEs can themselves trigger significant creep events on overlying crustal faults and is the first time such a creep event has been observed on the hazardous Wellington Fault that passes through New Zealand's capital city.

Although there is not yet geodetic evidence for episodic slow slip on the highly active (∼3 cm/year) Alpine Fault in the central South Island of New Zealand, there is tantalizing evidence that such behavior occurs there, in the form of tremor (Wech et al. 2012) and low-frequency earthquakes (Chamberlain et al. 2014). Tremor identified by Wech et al. (2012) appears to be located at 25–45 km depth, in a region of high P-wave attenuation (low Q_P) (Eberhart-Phillips et al. 2008) that may be the site of excess fluids near the deep extent of the Alpine Fault (Wannamaker et al. 2002). The low-frequency earthquakes, occurring at 20–30 km depth, are thought to represent slip on asperities within an otherwise steadily creeping portion of the Alpine Fault (Chamberlain et al. 2014). Tremor and low-frequency earthquake behavior are commonly observed in regions of episodic slow slip (e.g., Rogers & Dragert 2003, Obara et al. 2004) and may indicate that such behavior is also possible on the Alpine Fault. Denser cGPS networks as well as borehole strain and/or tilt are needed to resolve episodic SSEs on the Alpine Fault, if they exist.

5. COMPLEX INTERPLAY BETWEEN LARGE EARTHQUAKES AND HIKURANGI SLOW SLIP EVENTS

One of the most pressing challenges in the field of SSEs is to better resolve the relationship between SSEs and damaging earthquakes—complete understanding of this problem may eventually pave the way to use SSEs for better earthquake forecasting. A rich variety of complex interactions between SSEs and earthquakes have been observed at the Hikurangi subduction zone. This is likely due to the occurrence of several moderate to large earthquakes in the New Zealand region over the last ∼15 years, combined with the fact that a large depth range of the Hikurangi interface is amenable to land-based GPS and seismic monitoring so that these interactions can be recorded. These interactions include (*a*) SSEs being triggered by earthquakes (locally and remotely) (Francois-Holden et al. 2008; Koulali et al. 2017; Wallace et al. 2017, 2018), (*b*) M_w 5.5–6.5 earthquakes potentially being triggered by SSEs (Wallace et al. 2014, 2017; Koulali et al. 2017), and (*c*) the only observation to date of an earthquake halting an SSE (Wallace et al. 2014).

There have been several instances of earthquakes triggering SSEs at the Hikurangi subduction zone. The most remarkable of these is the triggering of widespread slow slip in nearly all of New Zealand's SSE regions (with the exception of Manawatu) by the 2016 M_w 7.8 Kaikōura earthquake (Wallace et al. 2017, 2018) (**Figure 9*a***). The 2016 Kapiti SSE, which was proximal to the Kaikōura earthquake rupture area, was likely triggered by large (>0.2 MPa) static Coulomb stress changes induced by the Kaikōura earthquake in the Kapiti SSE source (Wallace et al. 2018). However, the east coast SSE that was triggered immediately following the Kaikōura earthquake initiated at the northern Hikurangi margin, up to 600 km away from the earthquake rupture, where estimated static stress changes from the Kaikōura are exceedingly small (much less than 1 kPa). The east coast SSE was more likely triggered by dynamic stress changes from the passing seismic waves, which were amplified and prolonged by a basin effect arising from a large, low-velocity sedimentary wedge in the offshore outer forearc (Wallace et al. 2017; Kaneko et al. 2019).

Koulali et al. (2017) highlighted an unusual interaction between slow slip and earthquakes during a sequence of SSEs and an M_w 7.1 earthquake offshore of the North Island's northeast coast in August/September 2016. A large SSE began near Tolaga Bay (**Figure 9*b***) in late August 2016, 9 days before the September 2, 2016, M_w 7.1 earthquake struck northeast of the ongoing SSE, ∼50 km offshore of the Raukumara Peninsula (**Figure 9*b***). Based on the spatial and temporal proximity of the SSE to the earthquake, Koulali et al. (2017) suggested that the M_w 7.1 earthquake or an M5.7 foreshock may have been triggered by the SSE. Based on detailed investigation of the earthquakes in the sequence, Warren-Smith et al. (2018) prefer an interpretation that the SSE

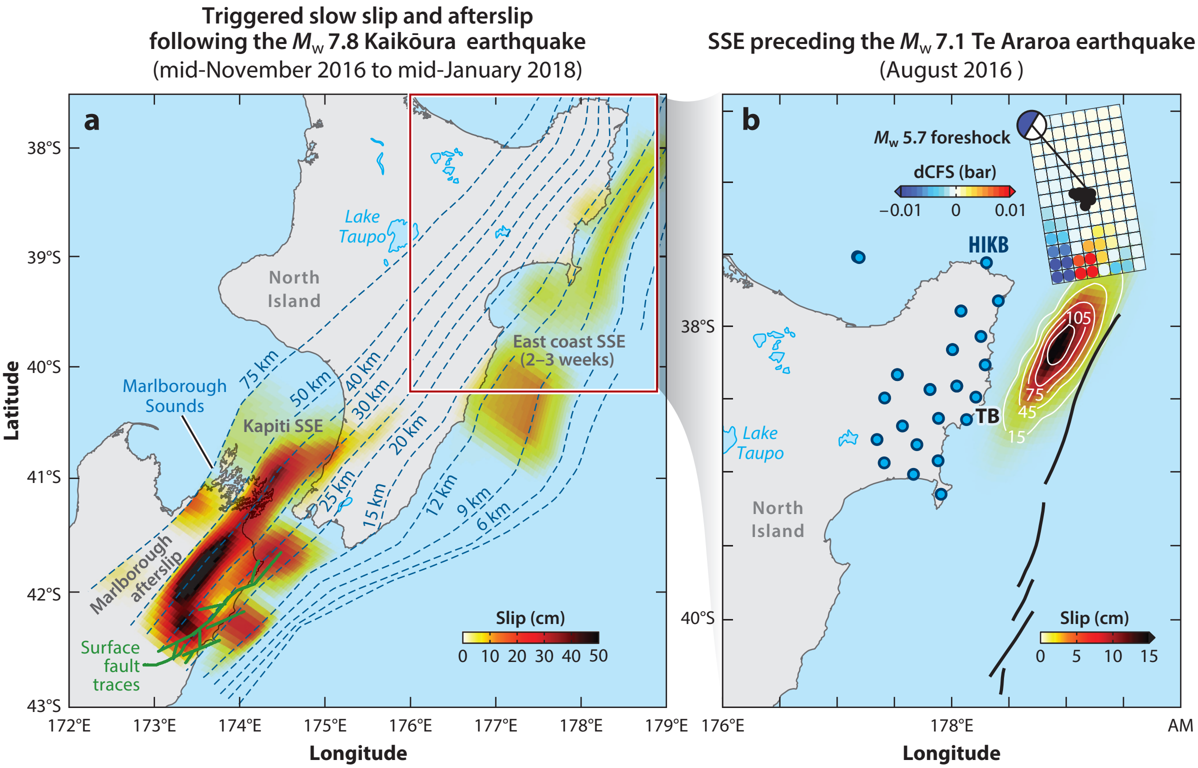

Figure 9

(*a*) Triggered slow slip and afterslip following the November 2016 M7.8 Kaikōura earthquake (see *color bar*). Shallow east coast SSEs finished within a few weeks following the earthquake, while the Kapiti SSE and afterslip in northern Marlborough persisted for more than a year (Wallace et al. 2018). Green lines show surface traces of faults that ruptured in the earthquake (Hamling et al. 2017). Panel adapted from Wallace et al. (2018). (*b*) Distribution of slow slip (*hot colors*) that preceded the August 2016 M_w 7.1 Te Araroa earthquake and its M5.7 foreshock, and the estimated change in Coulomb stress induced on the mainshock and foreshock fault plane by the SSE (*rainbow colors*). Also shown are foreshock (*blue focal mechanism*), aftershocks (*black dots*), and cGPS sites used (*dark blue dots*). Panel adapted from Koulali et al. (2017). Abbreviations: dCFS, Coulomb stress change; cGPS, continuously operating global positioning system; SSE, slow slip event; TB, Tolaga Bay.

triggered the M5.7 foreshock, which then dynamically triggered the M_w 7.1 mainshock. The Te Araroa earthquake itself also triggered a transient slip event in the far northern portion of the Hikurangi subduction zone, where SSEs had not previously been observed, and reinvigorated the ongoing SSE further south, causing it to become larger than SSEs observed in that region previously (Koulali et al. 2017).

The period 2013/2014 was one of large SSEs and numerous earthquakes in the lower North Island. A Kapiti SSE began in early 2013 (Wallace et al. 2014), and halfway through this SSE, a sequence of earthquakes in Cook Strait (just south of Wellington; up to M_w 6.6) (Hamling et al. 2014) occurred less than 50 km away. Given the proximity of the Kapiti SSE to the Cook Strait sequence, it is possible that static stress changes induced by the SSE in the Cook Strait region may have played a role in triggering of the earthquake sequence, although this is difficult to prove definitively. In late 2013 and early 2014, the Kapiti SSE migrated northward, into the Manawatu SSE source region. On January 20, 2014, the M_w 6.3 Eketahuna earthquake ruptured the subducting Pacific Plate just updip of the ongoing SSE. The 2013/2014 Kapiti to Manawatu SSE is estimated to have caused a Coulomb stress increase of ~0.03 MPa in the Eketahuna earthquake source, suggesting the possibility that the SSE triggered the M_w 6.3 Eketahuna earthquake. However, perhaps more intriguing is that the ongoing SSE was temporarily halted immediately following the Eketahuna earthquake (Wallace et al. 2014). Stress change modeling suggests that the Eketahuna earthquake caused a large increase in normal stress within the SSE source region, approximately 10 times greater than the shear stress change. Wallace et al. (2014) suggested that this clamping effect led to the temporary arrest of the SSE following the earthquake. To our knowledge, this is the only documented example to date of an earthquake halting an ongoing SSE.

6. WHAT CONTROLS ALONG-STRIKE VARIATIONS IN SLOW SLIP BEHAVIOR AND CHARACTERISTICS?

Most numerical modeling and observational studies suggest that episodic slow slip occurs in regions of transitional frictional behavior (e.g., the transition from seismic, velocity-weakening behavior to aseismic, velocity-strengthening behavior), in the presence of low effective stress due to excess pore fluid pressure (Liu & Rice 2007, Audet et al. 2009, Kodaira et al. 2004). Recent modeling studies have also shown that heterogeneity of frictional properties (Skarbek et al. 2012, Wei et al. 2013) and/or heterogeneous fault zone rheology (Ando et al. 2012, Lavier et al. 2013) can promote transient, slow slip behavior. Although the frictional stability transition is often thought to be a thermally controlled transition from brittle to ductile behavior in quartz-dominated lithologies (which typically occurs at ~350–450°C) (e.g., Oleskevich et al. 1999), the large along-strike variation in the depth of coupling and slow slip at the Hikurangi subduction zone suggests that the distribution of slow slip there is not thermally controlled (McCaffrey et al. 2008) and that other mechanisms must be at play. The along-strike changes in SSE distribution and interseismic coupling behavior at the Hikurangi subduction zone (**Figure 8**) offer a unique opportunity to evaluate the physical processes that control megathrust slip phenomena. A variety of changes (summarized below and in **Figure 10**) occur in concert with a shift from deep, long, and less frequent SSEs (and deep locking) at southern Hikurangi to a creep-dominated northern Hikurangi margin with frequent, large, shallow SSEs (Wallace et al. 2009).

The subducting plate becomes progressively rougher northward along the Hikurangi margin, where seamounts protrude above the sedimentary cover (which thins to <1 km), leading to an outer forearc dominated by subduction erosion, with only a steep, narrow active wedge (**Figure 1**). This contrasts with the southern and central portions of the margin, where the sediments on the subducting plate are thicker and a broad accretionary wedge has built out rapidly over the last 1–2 million years (Barnes et al. 2010). Wang & Bilek (2014) recognized a global correlation between a rough subducting plate and regions where the subduction interface is dominated by aseismic creep. They suggested that rough crust subduction leads to a highly heterogeneous distribution of stresses on the plate boundary, promoting a situation where much of the plate motion is accommodated by frequent, moderate seismicity and episodic SSEs. In contrast, it is thought that smoother subduction interfaces (where thick sediments are subducted) can lock up over large regions for hundreds of years, eventually resulting in a large earthquake (Ruff 1989). Given the correlation between shallow SSEs and a rough subducting plate at the northern Hikurangi margin, the heterogeneity of the shallow plate boundary may play a role in the occurrence of shallow slow slip there. In contrast, SSEs at the sediment-rich southern Hikurangi margin occur at the thermally controlled downdip transition from brittle to ductile behavior (McCaffrey et al. 2008), in a region where the plate interface is likely to be geometrically and compositionally more uniform, enabling broader, deeper zones of locking further updip. However, the correlation between a rough incoming plate and shallow SSEs is not perfect—the Hawkes Bay region

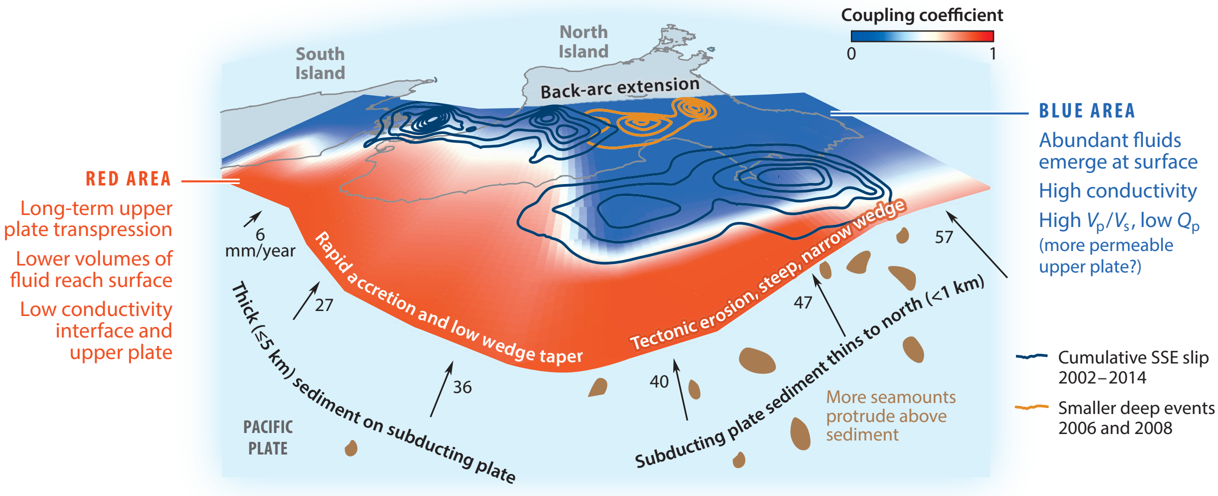

Figure 10

Summary of slow slip (*contours*), interseismic coupling (*red to blue colors*; see **Figure 8**), and along-strike changes in margin characteristics. Black arrows show convergence rates at trench (mm/year); brown shapes schematically show relative abundance of seamounts on the subducting plate. Abbreviation: SSE, slow slip event.

that hosts shallow, offshore SSEs (**Figure 6**) is also the site of a wide, well-developed accretionary wedge and relatively thick incoming sediment package, with fewer seamounts impacting the margin (**Figure 1**). It is important to note that the nature of the plate interface between Hawke Bay and Cape Turnagain is still poorly characterized, and the thickness of trench fill sediment does not necessarily correlate with the total volume of subducted sediment nor the smoothness of the plate interface.

Fluids are thought to influence the occurrence of SSEs through the control of fluid pressure on effective normal stress (Kodaira et al. 2004, Liu & Rice 2007, Audet et al. 2009, Warren-Smith et al. 2019). Magnetotelluric (MT) data acquired at the Hikurangi subduction zone reveal intriguing correlations between conductivity anomalies and regions of slow slip and locking (Heise et al. 2013, Heise et al. 2017). Regions of slow slip and creep at the northern Hikurangi subduction zone appear to coincide with areas of high conductivity/low resistivity on the plate interface, while locked areas have lower conductivity/high resistivity (Heise et al. 2017) (**Figure 11**). This can also be seen at a broader scale, where conductivity near the plate interface at the locked southern Hikurangi margin is markedly lower than the region of shallow slow slip and creep further north (Heise et al. 2013). The conductivity anomalies are interpreted by Heise et al. (2013, 2017) as being due to spatial variations in fluid content at the plate interface. Active and passive source seismic imaging reveals lower V_P, a higher V_P/V_S, and higher attenuation (low Q_P) of the overriding plate and plate interface in the regions of north and central Hikurangi shallow slow slip (Eberhart-Phillips et al. 2008, 2017; Eberhart-Phillips & Bannister 2015). Multichannel seismic data have also imaged packages of high-amplitude reflectivity at the plate interface in the SSE region offshore Gisborne; these are interpreted as fluid-rich underthrust sediments (Bell et al. 2010) (**Figure 5**). These observations contrast with the locked southern margin, where the overriding plate and plate interface region have higher V_P, lower V_P/V_S, and less attenuation

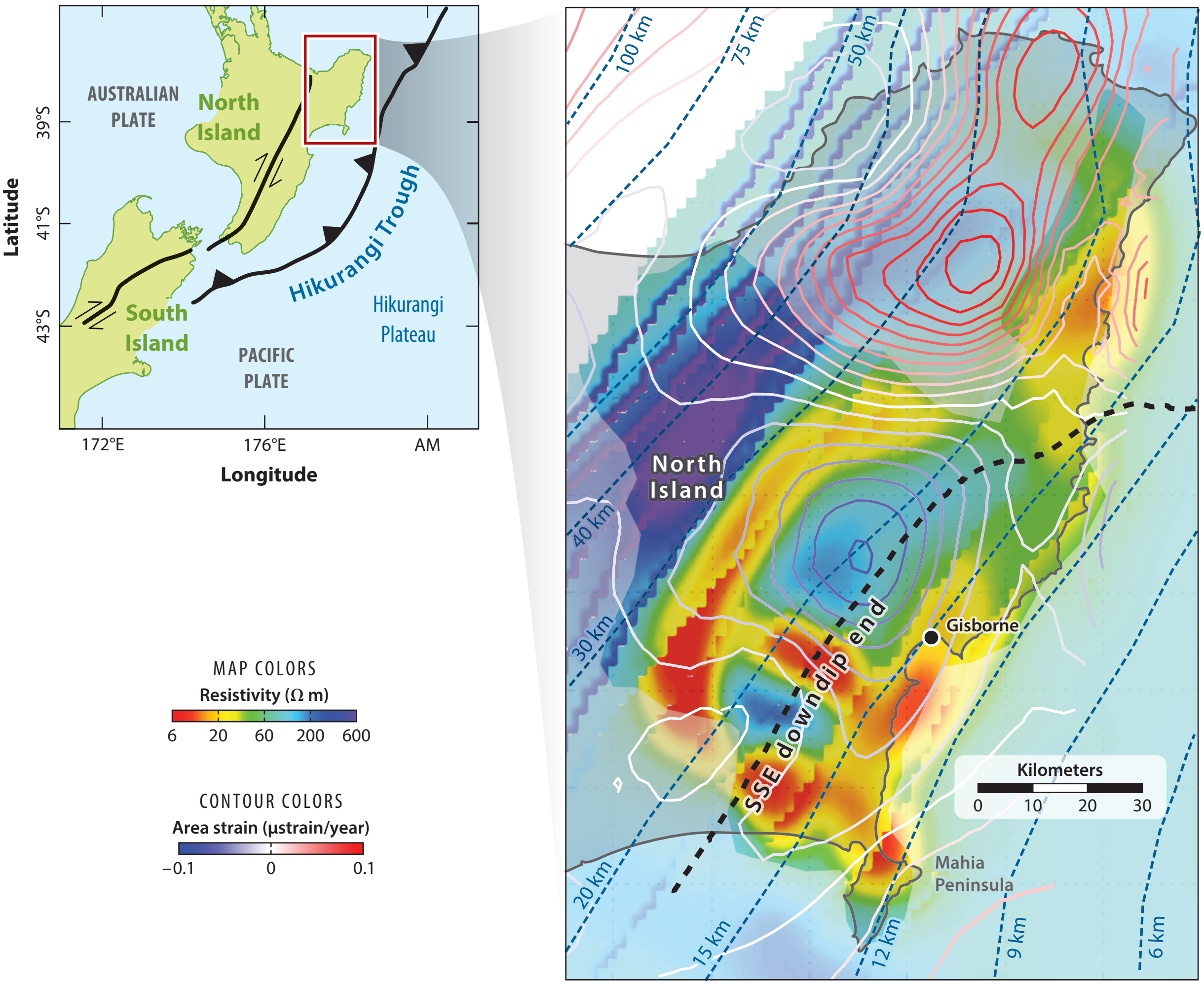

Figure 11

Resistivity (*upper scale bar*) of the plate interface at the northern Hikurangi subduction zone (Heise et al. 2017). Area strain rate is superimposed (*blue to red contours*, *lower scale bar*; Dimitrova et al. 2016); contraction is negative and overlies areas of locking, while pink to red contours overlie areas of creep and/or slow slip. The dashed black contour shows the approximate downdip end of SSEs in the Gisborne area; dashed blue contours show plate interface (depths in km below sea level). Abbreviation: SSE, slow slip event. Figure adapted from Heise et al. (2017).

(higher Q_P) (Bassett et al. 2014, Eberhart-Phillips & Bannister 2015, Eberhart-Phillips et al. 2017). Such changes in seismic characteristics have been previously interpreted to suggest a larger volume of fluids (and possibly higher fluid pressures) in the northern and central creeping portions of the Hikurangi subduction zone, relative to the locked portion further south (Bassett et al. 2014). It is also plausible that these variations in upper plate properties are related to possible changes in upper plate bedrock terranes, which are suggested to influence the degree of interseismic coupling (Reyners & Eberhart-Phillips 2009).

Geochemical data from onshore seeps and springs also suggest a major along-strike variation in the permeability of the upper plate and the source and abundance of fluids emerging at the surface (Reyes et al. 2010, Barnes et al. 2019). Barnes et al. (2019) showed a strong southward decrease in B, Li, Cl, and O concentrations in these seeps and springs and argued that this is due to lower permeability of the upper plate and increased interaction with ground water in the southern Hikurangi margin (relative to further north). It is possible that such changes in the signatures and volumes of fluids emerging in the forearc are related to the tectonic stress state and structural permeability of the forearc, which in turn may influence the state of interseismic coupling (Fagereng & Ellis 2009, Wallace et al. 2012c). This also raises a plausible interpretation that the observed changes in seismic properties (V_P/V_S and Q_P) reflect along-strike changes in interconnected fluids and permeability, rather than being due to excess fluid pressure as is widely assumed. Although there is strong evidence that the hydrogeological properties of the forearc and plate boundary vary in concert with coupling and SSE changes along the Hikurangi margin, the role that fluids play is not yet completely clear.

Overall, it is doubtful that one single factor (e.g., fluids, seamounts, overriding plate structure, incoming sediments, temperature) is wholly responsible for the observed distribution and characteristics of slow slip and locking at the Hikurangi subduction zone. Instead, it is likely that the interplay between these and other factors comes together to produce the observed behavior (e.g., Wallace et al. 2009). It is clear that the region of shallow SSEs is the site of varying degrees of geometric and lithologic heterogeneity of the subducting plate, with seismological and MT evidence for abundant, interconnected fluids and/or high fluid pressures near the interface and within the upper plate (Eberhart-Phillips et al. 2017, Heise et al. 2017) (**Figures 10** and **11**). In contrast, the southern, deeply locked plate boundary has a thick incoming sediment package being incorporated into a wide accretionary wedge (with fewer obvious geometric and lithological irregularities impacting the interface) (**Figure 1**) and with relatively lower conductivity near the locked plate boundary (Heise et al. 2013). Temperatures estimated in the SSE region at the southern Hikurangi margin are similar to deep SSEs elsewhere, so the position of deep southern Hikurangi SSEs is likely related to the thermal regime of the margin, as well as thick sediments on the incoming Pacific Plate that enable locking over a large area further updip.

Many aspects of Hikurangi SSE characteristics remain unexplained, such as the differences in duration and slip speed (short and fast in the north, long and slow in the south), and differences in recurrence intervals from north to south. Numerical modeling based on rate and state friction of long versus short duration SSEs in southwest Japan reproduced long duration SSEs with higher effective normal stress on the plate boundary, as opposed to shorter SSEs with lower effective normal stress (Matsuzawa et al. 2010). This could explain the depth-dependent variations in SSE duration observed at the Hikurangi margin (Wallace et al. 2012a), particularly given that normal stress increases with depth. It is also possible that the specific rock deformation mechanisms (such as pressure solution creep, dislocation creep, and diffusion creep) that dominate at different pressures and temperatures could strongly influence the magnitude and duration characteristics of the shallow versus deep SSEs at the Hikurangi margin. Recurrence intervals of SSEs at the Hikurangi margin also depend to some degree on the convergence rates (which increase northward) and the characteristic size of the SSEs (assuming that SSE slip is balanced by the accrual of elastic strain between SSEs). In general, we observe more frequent SSEs at the northern Hikurangi margin (every 1–2 years), where convergence rates are highest (**Figures 2–4**), while SSEs are less frequent in the south (every 5 years) (**Figure 3**), where convergence rates are the lowest, and the SSEs are largest. Overall, effective stress, temperatures, convergence rates, rock deformation mechanisms, and the frictional properties of the fault zone rocks all play important roles in determining the magnitude, duration, and recurrence characteristics of Hikurangi SSEs.

7. COMPARISON BETWEEN HIKURANGI MARGIN SLOW SLIP EVENTS AND GLOBAL SLOW SLIP EVENTS

A number of parallels can be drawn between the characteristics of SSEs at the Hikurangi margin and those at subduction zones elsewhere. Comparisons between these locales may help to resolve the physical controls on SSEs and their diverse characteristics. Shallow SSEs (e.g., <15 km deep) similar to those at the northern and central Hikurangi margin are observed most clearly in Ecuador (Vallée et al. 2013), Costa Rica (Dixon et al. 2014, Davis et al. 2015), and the Boso Peninsula in central Japan (Ozawa et al. 2007). In all of these locations, the shallow SSEs are relatively short (less than a few weeks); occur on portions of the interface with heterogeneous interseismic coupling (or creep); and occur where the subducting plate is studded with seamounts, which may be a feature common to most shallow SSE regions (Saffer & Wallace 2015). Shallow SSEs in Hikurangi, the Boso Peninsula, and Ecuador are usually accompanied by abundant microseismicity (Ozawa et al. 2007, Vallée et al. 2013, Jacobs et al. 2016). The relationship of microseismicity to shallow Costa Rica SSEs is less clear, although tremor is often observed there (Walter et al. 2013). The prevalence of microseismicity in association with many shallow SSEs may provide information about the scale of frictional heterogeneities in shallow SSE sources and the nature of frictional instability in these areas. There are also well-documented shallow SSEs updip of the seismogenic zone at the Nankai subduction zone (Araki et al. 2017), similar in magnitude to the small SSE observed updip of the locked portion of the southern Hikurangi subduction interface offshore the Wairarapa coast (Wallace et al. 2012a) (green dashed contours in **Figure 8**). These SSEs could be representative of slow slip occurring in the updip frictional transition—from velocity-weakening friction (in the locked region) to velocity-strengthening behavior closer to the trench.

The deep (>25 km), long-lived, infrequent SSEs in the Kapiti and Manawatu region share many characteristics with deep SSEs in Mexico (Guerrero region) (Radiguet et al. 2012), southwest Japan (Bungo Channel) (Hirose et al. 1999), and Alaska (Ohta et al. 2006). In all of these locations, the SSEs last more than one year, with infrequent recurrence intervals (5 years or more). Bungo Channel and Manawatu SSEs have particularly strong similarities, as both SSE regions occupy an along-strike transition from deep locking (beneath the southern North Island and Shikoku Island) to a mostly creeping plate boundary (central/north Hikurangi and Kyushu). This class of deep, long-term (e.g., >1 year) SSEs differ greatly from other well-studied, deep SSEs in southwest Japan and Cascadia, which are more frequent (at least once per year), shorter (less than a month), and accompanied by abundant tremor. The strong association between Cascadia and Nankai SSEs and tremor has led to them being termed episodic tremor and slip. Such strong association with tremor and deep SSEs is not yet clearly observed for New Zealand SSEs, with the possible exception of the deep Kaimanawa SSEs (e.g., Wallace & Eberhart-Phillips 2013) (**Figure 6**).

8. CONCLUSIONS

A number of unique characteristics of the Hikurangi subduction zone make it an important natural laboratory to investigate SSEs. Although episodic SSEs are well documented at the Hikurangi subduction zone, much work is needed to fully resolve the spectrum of slip behavior occurring there and the relationship of these transient deformation events to damaging earthquakes. An ever-increasing application of seafloor geodetic methods (including seafloor pressure and GPS-acoustic methods) (Bürgmann & Chadwell 2014, Wallace et al. 2016), InSAR (Bekaert et al. 2015, Hamling & Wallace 2015), and installation of onshore and offshore borehole instrumentation (e.g., Araki et al. 2017, Hawthorne & Bartlow 2018) are all needed to improve our ability to characterize transient deformation at the Hikurangi subduction zone over the coming years. There is also a need for high-fidelity characterization of the range of seismic phenomena associated with Hikurangi SSEs, including installation of borehole seismometers (with higher signal to noise) (e.g., Obara et al. 2004), deployments of dense arrays in targeted areas, and undertaking more OBS experiments in regions of offshore slow slip (Todd et al. 2018, Warren-Smith et al. 2019). Such efforts can reveal the spectrum of deformation processes occurring on the Hikurangi megathrust and the impact of SSEs on the likelihood of future earthquakes. Ultimately, improved understanding of the relationship between slow and seismic slip will facilitate incorporation of SSEs into more robust earthquake forecasts in New Zealand and elsewhere.

An even bigger challenge is to resolve the physical processes producing such a diverse assemblage of SSEs at the Hikurangi subduction zone. This has important implications for the processes behind SSE generation globally, a topic that geoscientists are only beginning to understand. Numerous experiments have been launched in the last few years to address these questions, including scientific ocean drilling across the source of SSEs at north Hikurangi (Saffer et al. 2018); high-resolution, 2D and 3D seismic imaging of the SSE source (MGL1801 Particip. 2018; **https://shire2017blog.wordpress.com/**); marine MT and controlled source electromagnetic surveys to image subsurface fluids (Chesley et al. 2019); and geochemical investigations of fluid flow above the source of SSEs (Solomon et al. 2018). Together, these and other investigations will take advantage of New Zealand's unique portal into the source of SSEs to answer some of the most important questions about the mechanisms behind slow slip occurrence. Over the next several years we expect that these and other research efforts focused on the Hikurangi subduction zone will transform our understanding of the origins of slow slip and the role that they play in the earthquake cycle at subduction zones.

SUMMARY POINTS

1. Similar to other subduction zones in the circum-Pacific, episodic, slow motion earthquakes lasting weeks to years have been observed at New Zealand's Hikurangi subduction zone using continuously operating global positioning system instruments.
2. Slow slip events in New Zealand exhibit an unusually diverse range of characteristics, with a range of magnitude, duration, and recurrence characteristics, which in many cases are depth dependent.
3. Seafloor geodetic methods using absolute pressure gauges reveal that slow slip at the northern Hikurangi subduction zone propagates to within less than 2 km of the seafloor at the Hikurangi Trough, making it the shallowest, well-documented subduction slow slip on Earth.
4. Seismological and geodetic investigations at the Hikurangi subduction zone have revealed a range of intriguing relationships between slow slip events and earthquakes in the New Zealand region.
5. The close proximity of slow slip events to the seafloor at the northern Hikurangi subduction zone, combined with the large, along-margin changes in interseismic coupling and slow slip behavior make the Hikurangi subduction zone a remarkable natural laboratory to investigate the physical processes that control earthquake and slow slip behavior on subduction plate boundaries.
6. A variety of factors may influence the occurrence of diverse slow slip and seismic behavior at the Hikurangi subduction zone, including thermal regime, thickness and properties of sediment on the subducting Pacific Plate, seamount subduction, physical properties and tectonic stress state within the upper plate, fluid pressure, and hydrogeological properties of the plate boundary zone, among many others.

FUTURE DIRECTIONS

1. Increased understanding of the relationships between earthquakes and slow slip events in New Zealand is needed to pave the way for better earthquake forecasting in the future.
2. Installing more sensitive instrumentation such as borehole strainmeters and borehole seismometers will expand our understanding of the full spectrum of slow slip and related seismic processes (such as tectonic tremor and low-frequency earthquakes) that occur in New Zealand.
3. Increased seismic, geodetic, and borehole instrument deployments beneath the ocean at the offshore Hikurangi subduction zone will transform our understanding of slow slip and earthquake processes near the trench—an important geohazards goal, as this is where tsunamis are generated.
4. Results from a large number of onshore and offshore experiments currently being undertaken at the Hikurangi subduction zone by the international scientific community will result in a step-change in our understanding of the mechanisms behind slow slip events and earthquakes at subduction zones over the next several years.

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